Cape Peninsula University of Technology

TECHNO-ECONOMIC ANALYSIS OF A LOW-COST BIOGAS FED COMBINED HEAT AND POWER SYSTEM FOR AFRICAN VILLAGES.

by

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DECLARATION

I, Rudzani Malange, declare that the contents of this dissertation/thesis represent my unaided work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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ABSTRACT

The increasing depletion of fossil fuels and the imperative of environmental sustainability have compelled the adoption of renewable energy sources (RES). Particularly, the utilization of renewable resources is crucial in African countries where challenges persist in accessing electricity and modern cooking fuels. Conventional electricity generation systems have proven inadequate to meet the growing energy demands within African villages due to the scarcity of fossil fuels. Consequently, this study examines the viability of alternative energy sources, focusing on the conversion of biomass into biogas through anaerobic digestion technology. Many African nations possess abundant biomass resources, making them potential feedstock for biogas production through commercial biogas plants. However, challenges such as startup finances and equipment shortages have hindered the full exploitation of these resources. This research addresses the feasibility of using anaerobic digestion to convert household and poultry waste from rural areas in Limpopo and Western Cape province, South Africa, into biogas for cooking, and lighting. The study employs two simulation models, one for the anaerobic digestion process and another for the subsequent power generation. Anaerobic digestion, a well-established technology for organic waste treatment, proves promising in this context. Research outcomes indicate that anaerobic digestion of kitchen and animal waste is a viable method for biogas production. Food waste amounting to 668 kg and 467.5 kg from Madombidzha village and Walladecene area produced a biogas volume of about 522.3 m^3 and 365.2 m^3, respectively while poultry waste amounting to 418 kg from Madombidzha village produced a volume of about 209 m^3. The results reveal that the more the waste the more biogas volume production. Employing the HOMER Pro hybrid microgrid system for electric power generation, the study demonstrates that the biomass from these rural areas can also be used in a biogas generator to generate electrical power. The estimated electric power production from the biogas generator in Madombidzha village and Wallacedene area amounts to about 109,508 kWh/year and 199,000 kWh/year, respectively. This investigation underscores the potential of anaerobic digestion as a sustainable energy solution, paving the way for the wider adoption of biogas technology in rural African communities.

Keywords: renewable energy, biomass, biogas, anaerobic digestion, electric power generation, sustainable energy, rural communities, African villages.

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DEDICATION

This work is dedicated to my beautiful baby girl, Imibulelo Renda. You have imparted greater strength, improvement, and contentment upon me than I could have ever envisioned. My affection for you knows no bounds.

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GLOSSARY

Renewable energy - Refers to energy derived from natural resources that are continuously replenished and are not depleted when used.

Biomass - Refers to organic materials like wood, agricultural leftovers, and animal excrement that can serve as a sustainable resource.

Anaerobic digestion - Is a biological process in which microorganisms break down organic matter, such as food waste or sewage, in the absence of oxygen to produce biogas.

Biogas - It's a sustainable energy source generated through the anaerobic decomposition of organic materials such as animal excrement, leftover food, and agricultural leftovers.

Power system - A network of electrical components and devices designed to generate, transmit, distribute, and control electricity, ensuring a reliable supply of electrical energy to meet various needs.

LIST OF ABBREVIATIONS

AD – Anaerobic Digestion

CHP – Combined Heat and Power

DGE - Digester gas engine

HRES – Hybrid renewable energy system

HOMER – Hybrid Optimization of Multiple Energy Resources

HRT – Hydraulic Retention Time

LBG – Liquid Biogas

NPV – Net Present Value

RES – Renewable Energy Resource

SA – South Africa

CHAPTER ONE
INTRODUCTION

1.1 Introduction

Renewable energy is an alternative source of energy that regenerates within a short period and can be extracted from the sun, either directly through thermal, photochemical, and photoelectric energy or indirectly through wind, hydropower, and photosynthetic energy stored in biomass (Cesaro and Belgiorno, 2015). In addition, renewable energy is clean with little or no greenhouse pollution. It is also sustainable as compared to other sources of energy such as coal, oil, and gas (Gao and Chen, 2023). Among several types of renewable energy, biomass is the only source of energy that is generated every day through household waste, animal waste, and sewage waste. Remarkably, biomass energy exhibits a distinct economic advantage over alternative energy sources, characterized by its comparatively lower cost and reduced expenditure (Elhouri, 2016). Hence, it is important to harness these resources for power generation. The Centre for Distributed Power and Electronics System (CDPES) in the Department of Electrical, Electronics & Computer Engineering at the Cape Peninsula University of Technology (CPUT) is actively involved in power generation using biomass resources. This study aims to develop a suitable biomass conversion system that can help to reduce energy poverty in rural villages across South Africa.

1.2 Research Background

In many African countries, getting electricity and modern cooking resources is still a big problem for homes and businesses (Kemausuor and Adaramola, 2018). Africa, particularly the Sub-Saharan region, is challenged with severe social, economic, and environmental difficulties. These difficulties include poor solid waste management, limited access to energy, and a heavy reliance on fossil fuels (Surroop, Bundhoo, and Raghoo, 2019). In numerous African nations, the existing energy generation infrastructure is insufficient to adequately satisfy the prevailing energy demand (Ang *et al.*, 2022). (Kemausuor and Adaramola, 2018) reported that sub-Saharan African (SSA) households constitute the majority of the over 2.7 billion people worldwide who rely primarily on traditional biomass for cooking. In 2014, only 38 percent of the population had access to electricity. Africa has less power generation capacity than other continents, but it's important to observe that energy development varies greatly among African nations. The region of SSA exhibits the lowest level of electrification globally, in contrast to Northern Africa which boasts nearly universal access to electricity (Quitzow and Jacobs, 2016). Unstable energy supply is a persistent issue in African countries. Regularly scheduled outages, known as load shedding, are common during Africa's electrical crises, in addition to unforeseen and irregular power outages caused by cable theft, acts of sabotage, or lightning strikes. These planned interruptions are the result of an ongoing imbalance between electricity generation and consumption. South Africa (SA) is one of the countries that has been dealing with a lengthy power outage and load shedding (Jahns, 2023). Apart from SA, other countries as Kenya, Tanzania, and Uganda encountered a significant electricity crisis characterized by the implementation of load-shedding measures. Ghana has also encountered numerous instances of electricity crises, with the most recent and severe occurrence transpiring from late 2012 to 2016 (Kupzig and Ackah, 2023).

In less-developed countries and SSA, more than 85 percent of people living in rural areas rely on wood and kerosene for cooking (World Health Organisation, 2009) (Ellabban, Abu-rub and Blaabjerg, 2014). These forms of energy sources serve as vital means for addressing cooking requirements and enabling the utilization of modern energy for lighting and mobile device charging. Notably, charcoal assumes a significant role in urban areas as a prevalent cooking fuel. Nevertheless, the utilization of wood and economically accessible charcoals as biofuels can have adverse consequences on human health due to the inhalation of smoke (The World Bank, 2005). The absence of modern energy infrastructure in rural areas has been identified as a contributing factor to school dropout rates, primarily attributable to the obligation of children to engage in the collection of firewood, which predominantly serves as a fuel source for cooking purposes. The provision of adequate access to modern energy resources has the potential to alleviate the time constraints imposed by the necessity of fuel gathering, consequently affording children increased opportunities for educational engagement and learning. Furthermore, the availability and affordability of energy resources facilitate an environment conducive to studying, irrespective of the time of day, whether during late hours or in the afternoon. These multifaceted benefits are anticipated to yield a noteworthy enhancement in the academic performance and overall pass rates of children residing in rural areas (Bank Group, 2017). Studies have confirmed that about seven million premature deaths happen every year due to outdoor and indoor air pollution. Clean energy can help to reduce the spread of diseases such as cardiovascular, respiratory, and stroke caused by smoke from dirty solid fuels used for cooking (Stecher, Brosowski, and Thran, 2013), (World Bank Group, 2017). African nations have significant chances to increase energy accessibility through their own renewable energy sources, in line with the rising global pattern. In 2016, contemporary renewable energy sources contributed to 10.4% of the world's total final energy consumption, while traditional biomass accounted for 7.8% (Kemausuor, Adaramola, and Morken, 2018). The modern renewable energy share included energy generated from biomass fuels, such as solid biomass and biogas for electricity and heat generation using modern technologies. The use of solid wastes as feedstock for energy generation electricity, cooking fuel, or transport fuel is not widely used in Africa, although some exceptions do exist (Kemausuor and Adaramola, 2018).

1.3 Problem Statement

The generation of electric power through conventional systems can no longer sustain the increasing demands in African villages due to the scarcity of fossil fuels. This development prompted an investigation into alternative sources of energy such as Biomass. For this purpose, this study aims to develop a low-cost biogas conversion system that uses an anaerobic digester to convert the Biomass (household waste) extracted from these rural villages into biogas for electric power generation, cooking, and lighting. The analysis will be conducted using HOMER Pro and MATLAB software.

1.4 Aims and Objective.

The study aims to investigate and analyze a low-cost biogas-fed combined heat and power system using household wastes extracted from African villages**.**

The objectives of the research are as follows:

- To investigate how much household waste are produced in a day/week in rural African villages.
- To design and model a system using an Anaerobic digester to convert biomass from household wastes into biogas for cooking.
- To design a hybrid microgrid system for biomass to electric power generation for lighting and cooking and perform a techno-economic analysis of the proposed system.

1.5 Research Delineation

The focus of this study is to use a biological transformation method that consists of Alcoholic fermentation and Anaerobic Fermentation. The study is simulation based. The data collected is collected from two villages in Limpopo provinces and the Wallacede area.

1.6 Summary of the chapters

Chapter 1 presents the background of the research, statement of the research problem aims and objectives, and the research delineation.

Chapter 2 presents the literature reviews on energy resources and conversion methods. The chapter delves into an examination of renewable energy resources, with a specific emphasis on biomass and its transformation technologies for energy generation.

Chapter 3 presents the proposed methods chosen for this study.

Chapter 4 gives the design and modeling of a low-cost biogas-fed system using the Anaerobic method and hybrid microgrid system. The chapter concludes by comparing the simulation results with the literature.

Chapter 5 concludes the study. It summarises the findings of the research and gives future recommendations.

CHAPTER TWO
RENEWABLE ENERGY RESOURCES

2.1. Introduction

This chapter provides an in-depth explanation of renewable energy sources, with a particular emphasis on biomass energy as a significant renewable energy portfolio component. The study examines various aspects of biomass energy, such as its potential as a renewable and environmentally favorable energy source. In addition, the chapter explores the technologies used to convert biomass into biofuels and electric power, contributing to an understanding of the transformational pathways that allow for its incorporation into energy balances.

2.2 Renewable Energy Sources

Renewable energy sources (RES), also referred to as alternative energy sources, encompass a range of energy sources that can be replenished, produce energy repeatedly, and are inexhaustible (Ellabban, Abu-rub and Blaabjerg, 2014), (Halkos, 2020). These sources include solar energy, wind energy, bioenergy, geothermal energy, hydropower, and ocean energy. They can be harnessed for various purposes such as power generation, transportation, domestic use, and urban heating (Holt and Pengelly, 2008), (Halkos, 2020). Historically, fossil fuels were the primary source of worldwide electrical generation. According to the International Energy Agency's (IEA) World Energy Outlook 2015 report, fossil fuels account for around 67% of worldwide electricity production (Halkos, 2020), (Aboagye *et al.*, 2021). However, due to the negative environmental effects of fossil fuel-based power generation, such as climate change, the depletion of fossil fuel reserves, and fluctuating pricing, a move towards higher use of renewable energy resources for the world's electrical supply is required (Chakraborty *et al.*, 2012), (Ellabban, Abu-rub and Blaabjerg, 2014), (Aboagye *et al.*, 2021). Figure 2.1 shows the different types of renewable and non-renewable resources (Elhouri, 2016).

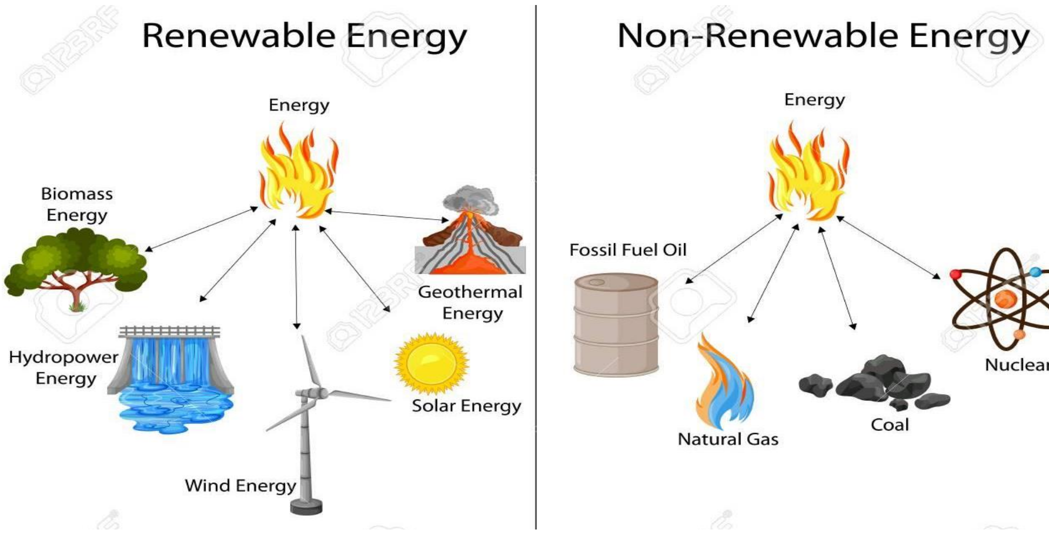


Figure 2. 1: Types of renewable energy and non-renewable energy

(Elhouri, 2016)

Governments across the globe are progressively directing their attention towards Renewable Energy Sources (RES), primarily owing to the manifold advantages they offer in comparison to fossil fuels (Aboagye *et al.*, 2021). They help to improve environmental quality by generating little or no greenhouse gases (GHG) (Elhouri, 2016), (Ibrahim et al., 2021). Additionally, they are available in practically every region on the planet, they provide equal energy distribution, solving energy security and energy poverty concerns. Furthermore, RES are deemed more reliable than fossil fuels, and they have lower operational costs and economic benefits. RES helps to boost employment and stabilize energy prices at the macroeconomic level (Ibrahim *et al.*, 2021). These sources have the potential to improve the living conditions of households and satisfy most of their energy requirements without depletion. In addition, research indicates that renewable energy sources have positive effects on human health, as their lower GHG emissions are associated with fewer health problems than fossil fuels (Ellabban, Abu-rub, and Blaabjerg, 2014) (Halkos, 2020). Nevertheless, RES have some disadvantages. Initial costs associated with implementing these sources can be prohibitive for potential consumers. Moreover, the cost of energy storage systems is considerable. Furthermore, renewable energy is dependent on the weather, and protracted periods of unpredictability in weather patterns can result in energy shortages. Despite these obstacles, RES are widely regarded as the best option for meeting global energy demands, reducing excessive fossil fuel consumption, and achieving the seventh Sustainable Development Goal (SDG) of ensuring access to affordable, sustainable energy (Halkos, 2020).

2.2.1 Biomass as a renewable energy

Biomass is any organic matter, usually plant-based, usable on a regenerative or recurring basis (Agency, 2007) (Elhouri, 2016). Biomass consists of all land and water-based vegetation and trees, as well as all waste biomass, including forestry and agricultural residues, municipal bio-solids (sewage), municipal solid waste (MSW), animal wastes (manures), domestic kitchen waste, and certain types of industrial wastes (David *et al.*, 2019) (Jekayinfa and Orisaleye, 2020). Biomass is also called substrate because it is suitable to be used for several fermentation purposes (Steinhauser, 2011). Table 2.1 shows some of the substrates that can be used for biogas yield (BY).

Table 2. 1 Substrate for biogas yield production

Residual from beverage production	**Animal waste**	**Greens, grass, cereal, Vegetable waste**	**Waste from food & fodder industries**	**Waste from households**	**Livestock productive**
Apple mash	Meat and bone meal	Leaves	Potato mash, potato peeling	Leftovers (Kitchen or Canteen)	Liquid manure from cattle
Spent fruits	Animal fat	Maize straw	Mash from fruits	Dry bread	Excreta from cattle
Spent apples	Slaughterh ouse waste	Grass cuttings from lawns	Cereal mash	Sewage sludge (households)	Excreta from pigs
Beer	Blood Liquid	Hay	Wheat flour	Mixed fat	Excreta from chickens
Spent grain	Blood meal	Market waste	Wheat bran	Scum	Liquid manure from pigs

The expanding interest in biomass energy may be a result of the advantages it possesses over other energy sources. First, biomass energy can be used for a variety of applications, including cooking, heating, electricity generation, and transportation. Biomass energy is the only renewable energy form that can be converted into liquid fuel. Secondly, biomass energy is renewable, abundant, and simple to produce (Wang *et al.*, 2020). In many developing nations, biomass contributes to almost 35 percent of the energy demand, and its global consumption has increased by 13% (Wasif *et al.*, 2021).

Biomass can be converted into various bioenergy through conventional technologies that will be discussed in the next subsection. The selection of the conversion method is impacted by various elements, including the kind, amount, and properties of biomass feedstock, the preferred energy form or end-use needs, environmental regulations, governmental policies, economic circumstances, and unique project-related considerations. In most cases, the appropriate process route is determined by the form of energy required and the availability of feedstocks (Adams *et al.*, 2018).

2.2.2 Biomass conversion technologies

Biomass can be harnessed through two primary pathways, direct utilization via combustion for heat generation or indirect utilization following conversion into various biofuels (Adams *et al.*, 2018), (David *et al.*, 2019). The term "bioenergy" refers to the energy that is obtained from biomass feedstocks. The biorefinery system operates by utilizing biomass as the primary input material (feedstock) for the manufacturing of various biobased products. The fundamental principle underlying the biorefinery system involves the production of biofuel and a platform of chemicals derived from biomass (Chakraborty *et al.*, 2012). Conversion of biomass to biofuel can be obtained by various methods (Deubien and Steinhauser, 2011), (Pradesh and Maurya, 2014), (Mwangomo, 2018). The conversion of biomass into a viable energy source necessitates the completion of various stages, including but not limited to harvesting, drying, storage, transportation, and processing (Adams *et al.*, 2018). There are three main process technologies employed in the conversion of biomass into energy: bio-chemical, thermo-chemical, and physio-chemical (Lee *et al.*, 2019). The field of biochemical conversion involves two primary process alternatives: anaerobic digestion (AD), which generates biogas consisting primarily of methane and carbon dioxide, and fermentation, which produces ethanol. Thermo-chemical conversion incorporates four primary process options, namely combustion, pyrolysis, gasification, and liquefaction. The physio-chemical conversion process primarily involves the extraction of oil from oilseeds through the process of crushing, followed by esterification (Lee *et al.*, 2019). Figure 2.2 shows a detailed flow chart on the conversion processes such as physical, chemical, biological, and thermal or a combination of processes with their end products.

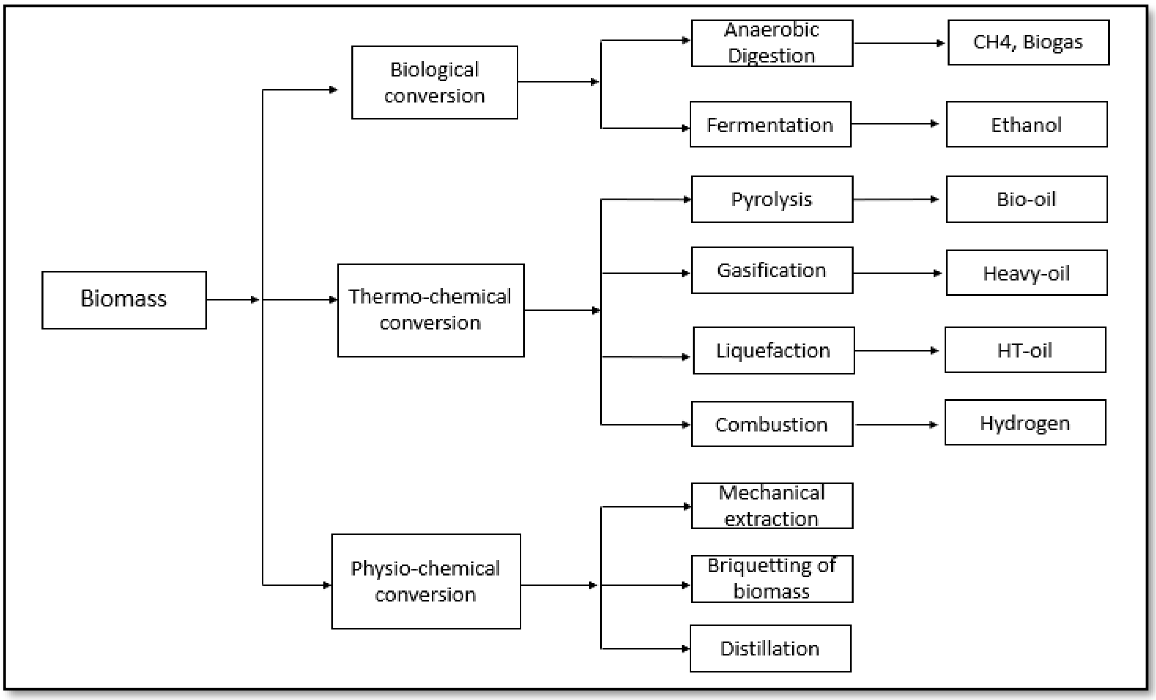


Figure 2. 2: Applied technologies to transform biomass into different energy sources.

The subsequent sub-sections give an overview of each of the main energy conversion alternatives.

2.2.2.1 Biological conversion

This conversion process involves two main process options: anaerobic digestion (AD) (production of biogas, a mixture of mainly methane and carbon dioxide) and fermentation (production of ethanol). AD is the process of converting organic matter (feedstock) into a gas known as biogas. Biogas primarily consists of methane and carbon dioxide, along with trace amounts of other gases like hydrogen sulfide (Adams *et al.*, 2018). Feedstock from cattle, donkeys, goats, sheep, and chicken, as well as kitchen refuse and human waste can be utilized effectively to produce biogas energy (Mkhabela, Mukumba, and Makaka, 2020).

The primary outputs generated during this process include methane, fertilizer, and carbon dioxide. AD is a process that yields biogas, which can be utilized for the generation of electricity and/or heat. Additionally, the biogas can be refined into biomethane and introduced into the gas grid or employed as a fuel for transportation purposes (Mukumba, Makaka, and Mamphweli, 2017), (Mkhabela, Mukumba and Makaka, 2020). Fermentation is an anaerobic biological process wherein the conversion of simple sugars derived from biomass feedstock into alcohol and carbon dioxide is facilitated by a distinct group of microorganisms, typically yeasts (Adams *et al.*, 2018). For ages, people have employed yeasts and other microorganisms to convert plant sugars into ethanol (Khan *et al.*, 2015). Fermentation is widely utilized commercially in many countries to manufacture ethanol from sugar crops (sugar cane and sugar beetroot) and starch crops (maize and wheat) (Khan *et al.*, 2015).

2.2.2.2 Thermo-chemical conversion

Biomass can undergo thermochemical conversion via pyrolysis, gasification, liquefaction, and combustion (Chiappero *et al.*, 2020). Pyrolysis serves as the initial phase in various thermo-chemical processes, as it involves chemical reactions that result in the formation of solid, liquid, and gaseous products in the absence of oxygen (Fatehi *et al.*, 2021). Pyrolysis is a chemical phenomenon characterized by the thermal degradation of organic substances under elevated temperatures, typically in an oxygen-deficient or oxygen-limited environment. Thermal degradation is a process characterized by the breakdown of intricate molecules into smaller, less complex compounds. Under normal circumstances, the presence of oxygen is necessary for the material to undergo combustion or burn. However, in the absence of oxygen, this process is prevented. Conversely, the substance undergoes thermal decomposition. The composition of the pyrolysis products acquired is contingent upon both the characteristics of the feedstock utilized and the specific conditions employed during the process. Bio-oil is typically the primary output of the pyrolysis process (Lee *et al.*, 2019).

Gasification is a thermochemical procedure that transforms carbon-based substances, including coal, biomass, and municipal solid waste, into a composite of gases referred to as syngas, or synthesis gas. Gasification, in contrast to pyrolysis, takes place under controlled conditions with the presence of a specific quantity of oxygen or steam (Damartzis and Zabaniotou, 2011). During the gasification process, the feedstock undergoes thermal treatment within a gasifier, where it is exposed to elevated temperatures typically within the range of 700 to 1,500 degrees Celsius (1,292 to 2,732 degrees Fahrenheit). The gasifier is a reactor that has been specifically designed to facilitate a sequence of chemical reactions on the feedstock. The reactions entail the partial oxidation or partial combustion of carbon-based substances, leading to the generation of syngas (Khan *et al.*, 2015). The syngas generated during the gasification process possess versatile applications. It possesses a wide range of applications as a fuel source, capable of direct combustion in engines or turbines to facilitate the generation of electricity. Syngas possesses the potential to serve as a valuable feedstock in the manufacturing processes of various chemicals, fertilizers, and transportation fuels. Furthermore, it can undergo additional processing to effectively eliminate impurities and contaminants prior to its utilization (Chiappero *et al.*, 2020).

The process of liquefaction entails the conversion of a substance from either a gaseous or solid state to a liquid state through the application of cooling or compression techniques (Fatehi *et al.*, 2021) (Jha *et al.*, 2022). The selection of a particular method is contingent upon the inherent characteristics of the substance under consideration as well as the intended objective. The process of liquefaction exhibits variability contingent upon the specific substance under consideration. Liquefaction exhibits practical utility across diverse domains. In the energy sector, it is common practice to convert natural gas into liquefied natural gas (LNG) for storage and transportation, thereby enabling its efficient conveyance across extensive distances. Likewise, the process of air liquefaction finds application in the manufacturing of liquid oxygen, nitrogen, and various other industrial gases. The process of substance liquefaction in the fields of chemistry and pharmaceutical manufacturing facilitates enhanced manageability, storage capabilities, and controlled reactivity (Bridgwater and D.G, 1993).

Direct combustion is one of the most straightforward methods for converting biomass to energy. Industrial biomass combustion facilities can burn many types of biomass fuel, including wood, agricultural residues, wood pulping liquor, municipal solid waste (MSW), and refuse-derived fuel in a high-pressure boiler to generate steam. The steam turns a turbine, which powers a generator, to generate energy (Khan *et al.*, 2015), (Ben Brahim and Thiry, 1999). The steam turbine's exhaust can be fully condensed to generate electricity or used for another useful heating activity. Biomass can be co-fired with coal in a coal-fired power station, in addition to being used exclusively to power a steam turbine (Ben Brahim and Thiry, 1999). Only certain types of biomass materials are used for direct combustion because of the potential for ash build-up within the system (which fouls boilers, diminishes efficiency, and raises costs) (Khan *et al.*, 2015).

2.2.2.3 Physio-chemical conversion

Physio-chemical conversion, alternatively known as mechanical extraction, is a mechanical process employed to extract oil from the seeds of diverse biomass crops, including oilseed rape (OSR) and linseed. The aforementioned procedure yields a liquid fuel that can subsequently undergo a subsequent phase referred to as esterification, wherein the oil is converted into fatty acid methyl ester, commonly recognized as biodiesel (Chiappero *et al.*, 2020). The process yields both oil and a residual solid substance commonly referred to as 'cake', which possesses suitable properties for utilization as animal fodder. The utilization of this technology is prevalent across Europe, wherein vegetable oils derived from crops, particularly oilseed rape (OSR), are predominantly employed. However, waste fats and oils are also utilized in this context. The primary application of biodiesel pertains to its utilization as a liquid fuel for transportation purposes, typically in conjunction with petroleum-derived diesel through blending (Adams *et al.*, 2018).

There are several commercials, proven, and cost-effective technologies that are available to convert biomass feedstock into heating or electricity. The most important part for plant owners is to check if the technology they are choosing is commercial and proven as it can affect the production of electricity or heat. The use of developed and commercial technologies is therefore important for the project's financial feasibility and reliability and thus affects funding possibilities (With, 2017).

2.2.3 Biogas to Electric Power Production

Access to energy that is affordable, sustainable, and dependable is crucial for enhancing rural poor people's living conditions, economic growth, and development. Biogas is entirely capable of replacing wood, hard coal, kerosene, plant residues, and propane as rural energy sources (Olugasa, Odesola, and Oyewola, 2014). Biogas derived from AD is a promising source of clean energy with the potential for diverse end-use applications, including direct combustion (cooking/heating and lighting), combustion in a CHP (cogeneration) facility to produce electricity and heat, and upgrading to natural gas quality (Olugasa, Odesola and Oyewola, 2014), (Uddin *et al.*, 2016). The processed biogas can be used in a gas turbine for electricity production, in a heat-producing boiler, or in a combined heat and power plant (CHP) for heating and power generation (Lindkvist, 2020).

2.2.3.1 Gas Turbine system for electricity production

The gas turbine in Figure 2.3 is technically a simple device that depends upon fuel combustion. To accomplish this, a working fluid (gas) is necessary and pressurized by a compressor. The fuel combustion in a chamber supplies heat by homogenous combustion, but catalytic or even indirect heating is possible. The heating of the gas raises the temperature and kinetic energy. The turbines produce work by the transfer of hot expanding gas. The bulk of the work is used to power the compressor, and the remainder is to drive an electric generator that produces power (Pointon and Langan, 2002).

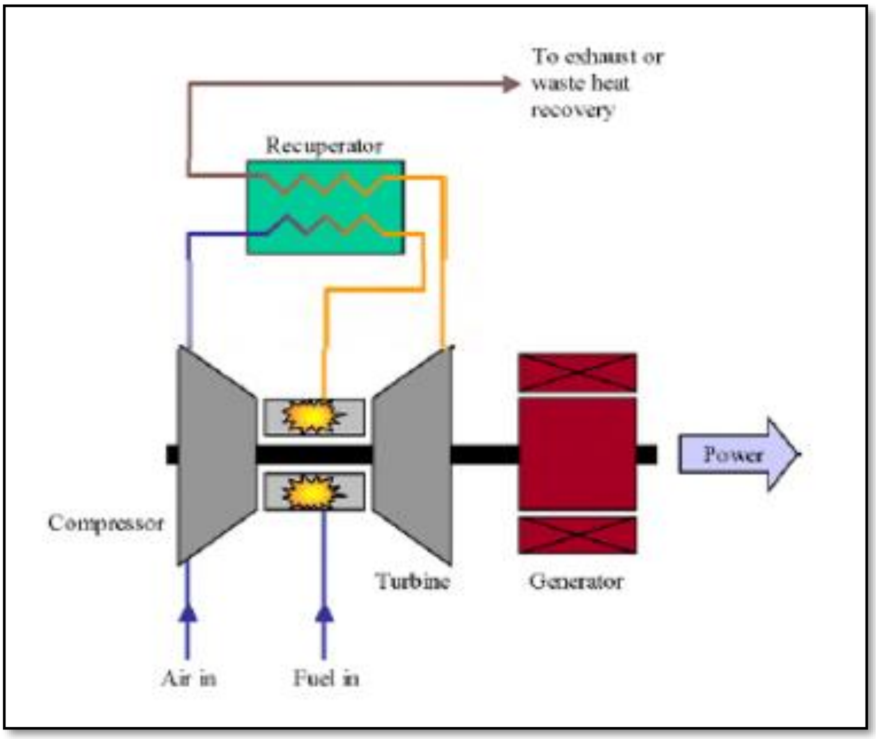


Figure 2. 3:Gas Turbine system

(Pointon and Langan, 2002

2.2.3.2 Combined Heat and Power

Combined heat and power (CHP) systems, along with energy storage technologies, play a crucial role in enhancing the equilibrium and efficiency of renewable energy systems. CHP systems not only provide a valuable alternative to traditional systems that separately produce heat and power but also enhance the energy efficiency and resource-saving attributes of energy systems. Additionally, integrating CHP systems with renewable energy sources (RES) enhances their sustainability while reducing greenhouse gas emissions (Razmi *et al.*, 2021). CHP systems integrate heat and cooling power production and electricity into one operation, using much fewer fuels than when heat and energy are generated separately (Macadam and Cox, 2008).

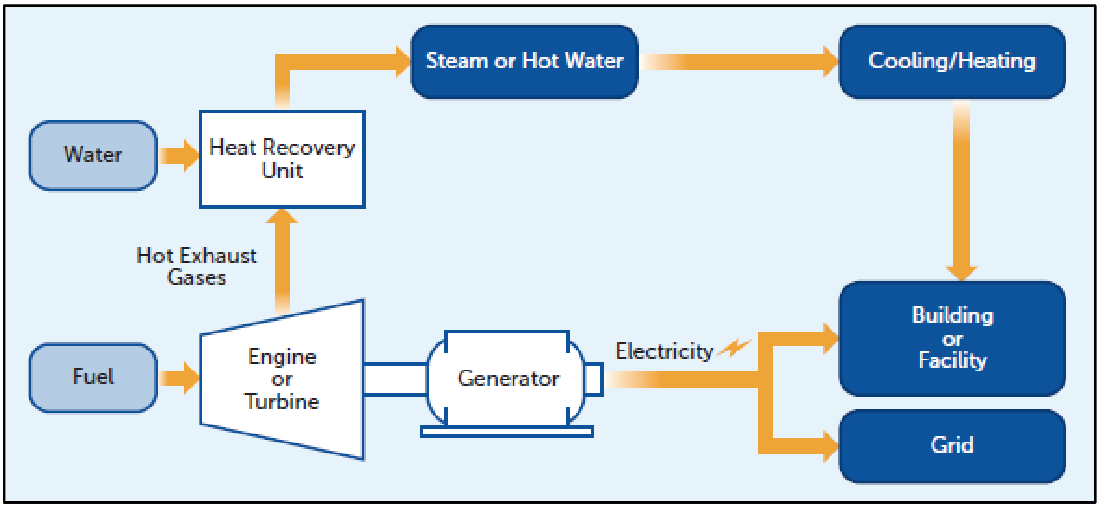


Figure 2. 4:Typical topping cycle gas turbine CHP

(U.S. Environmental Protection Agency, 2014)

The CHP systems consist of several components: heat engines, generators, heat recovery, and electrical connections, as shown in Figure 2.4. The recovery of thermal energy that is otherwise lost to generate usable thermal energy or electricity is a part of any CHP application. The configuration of the CHP systems can be designed either as a topping or a bottoming cycle. (U.S. Environmental Protection Agency, 2014).

In a typical topping cycle system, fuel is burned in a heat engine such as a gas turbine or reciprocating engine to generate electricity. The energy usually lost in the hot exhaust and refrigeration systems of the main driver is instead recovered to provide heat for industrial processes (for example, processing of petroleum or food), hot water (for laundry and dishwasher), spacious heating, refrigeration, and dehumidification. The burnt fuel provides thermal input to a furnace or another industrial process in the bottoming cycle method called (waste heat at power) whose application is for electricity generation (U.S. Environmental Protection Agency, 2014).

2.4 Conclusion

This chapter has presented a complete overview of RES, with a particular emphasis on biomass energy. RES such as biomass, have various advantages, including lower greenhouse gas emissions, wider availability, equitable energy distribution, and economic benefits. Despite some limitations, such as early costs and weather dependence, renewable energy is regarded as critical for meeting global energy targets and attaining sustainable development. The chapter discussed biomass conversion processes, such as biological, thermochemical, and physiochemical approaches. These methods allow biomass to be converted into useful forms of energy such as biofuels and electricity. With its numerous conversion paths and applications, biomass energy shows promise as a sustainable and ecologically friendly energy source that may greatly contribute to satisfying energy demands while minimizing environmental concerns. As the globe seeks cleaner and more sustainable energy options, biomass energy research and utilization will surely play an important role in creating a greener future.

CHAPTER THREE
ANAEROBIC DIGESTION METHOD AND IMPLEMENTATION

3.1. Introduction

This chapter provides a thorough explanation of the method chosen for this study, namely anaerobic digestion. A comprehensive review of the anaerobic digestion process will be provided to facilitate comprehension of its application in the context of research. In addition, the responsibilities and capabilities of the software tools utilized in this research will be described. In addition, the geographical regions or areas chosen as the focus of this investigation will be discussed, along with the rationale for their selection and their significance within the overall framework of the investigation.

3.2. Anaerobic digestion process

Anaerobic digestion (AD) is a natural process that breaks down complex organic materials into simpler chemicals without needing oxygen (Li *et al.*, 2023). During this process, a gas that is mainly composed of methane (CH_4) and carbon dioxide (C_O2), also referred to as biogas, is produced as the end products under ideal conditions (Pramanik *et al.*, 2019), (Curry and Pillay, 2012). When an AD plant produces biogas, a trace amount of hydrogen sulphide $((H_2S)$, ammonia (NH_3), and other gases are also present. As a multistep biochemical process, the AD process can be divided into four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Kothari *et al.*, 2014) (Pramanik *et al.*, 2019) as shown in Figure 3.1 below.

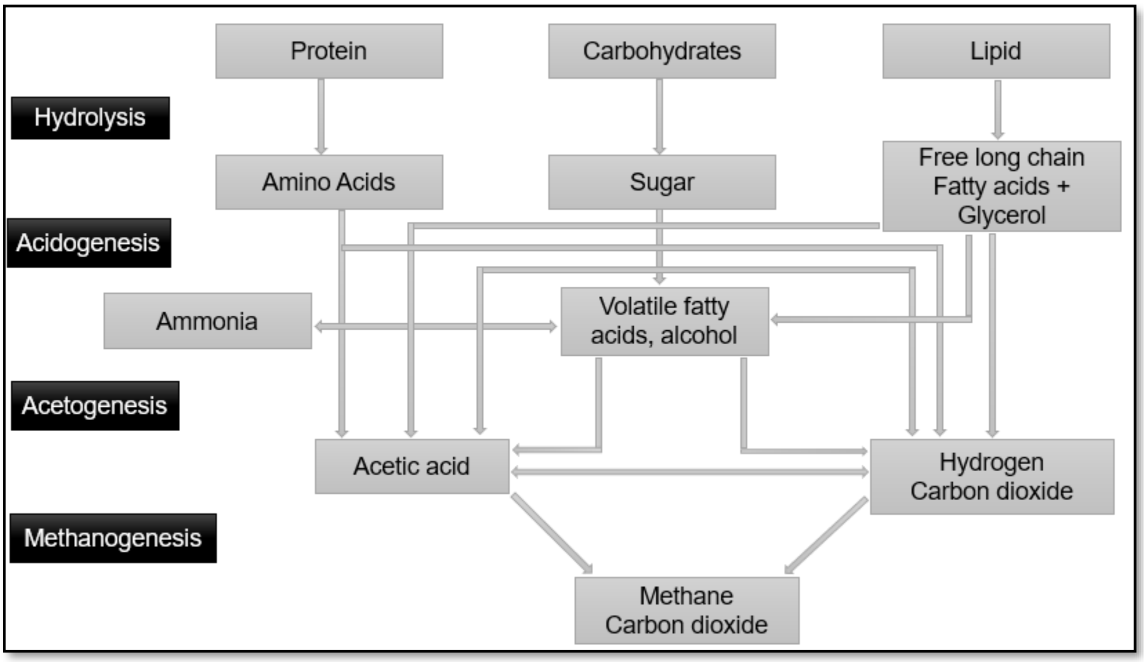


Figure 3. 1:Anaerobic digestion process stages

During the process of acidogenesis, the hydrolysis of various substances, including sugars, amino acids, and fatty acids, leads to the formation of monomers and dissolved compounds.

These compounds are subsequently transformed into simpler molecules with relatively low molecular weights, such as volatile fatty acids (e.g., propionic, butyric, and acetic acid), alcohols, and various gases (including carbon dioxide (C_O2), hydrogen, and ammonia) (Elsamadony *et al.*, 2021). During the subsequent phase, a different set of acidogenic microorganisms engage in the fermentation process, converting the breakdown products into hydrogen, carbon dioxide, and small-sized volatile organic acids, such as acetic, propionic, and butyric acids (Li *et al.*, 2023) (das Neves, Converti and Penna, 2009) (Li, Chen and Wu, 2019). During the third stage, the substances undergo a conversion process facilitated by acetogenic bacteria, resulting in the production of acetic acid. During the final stage, methanogenic bacteria facilitate the conversion of acetic acid, hydrogen, and carbon dioxide into a composite of methane and carbon dioxide, commonly referred to as "biogas" (das Neves, Converti and Penna, 2009) (Li, Chen and Wu, 2019). Methane (CH_4)is produced by methanogenic bacteria of two main metabolic kinds. The "acetoclastic" methanobacteria degrade acetic acid into methane and carbon dioxide, accounting for over 70% of biogas methane concentration. The "hydrogenotrophic" bacteria use hydrogen (H_2) as an electron donor to convert C_O2 to CH_4 accounting for most of the residual methane production. Other methano bacteria can create methane in lower amounts from formic, propionic, and butyric acids, as well as other chemical precursors (Das Neves, Converti, and Penna, 2009) (Ali and Stu, 2018).

3.3. Feedstock for Anaerobic digestion

In theory, a wide range of biological feedstock varieties have the potential to produce biogas. Biogas is a composite of various gases, including methane, and carbon dioxide, as well as additional gases like hydrogen sulphide (H_2S) and ammonia (NH_3) (Li *et al.*, 2023). However, the substrate often is chosen based on the raw material's availability, the nature of the substrate, the type of digester, and its operating parameters (Kothari *et al.*, 2014). The most common typical feedstock used for biogas production are animal manure and slurries, human waste excreta, agricultural crop and remains, food industries and dairy production wastes, the organic fraction of municipal solid wastes (MSW), wastewater sludge, and household wastes (Kothari *et al.*, 2014), (Li *et al.*, 2023). The biogas yield is the volume of biogas that can be generated from a unit of mass of a specific feedstock. Substrates with a high concentration of sugars and fatty acids provide a relatively high biogas production. Furthermore, the percentage of CH_4 generated from the resulting biogas varies depending on the type of biomass material used. Thus, biogas output is determined by the total mixture of components fed into the bio-digester (Zalm, 2017). Figure 3.2 shows feedstocks that can be used for biogas production.

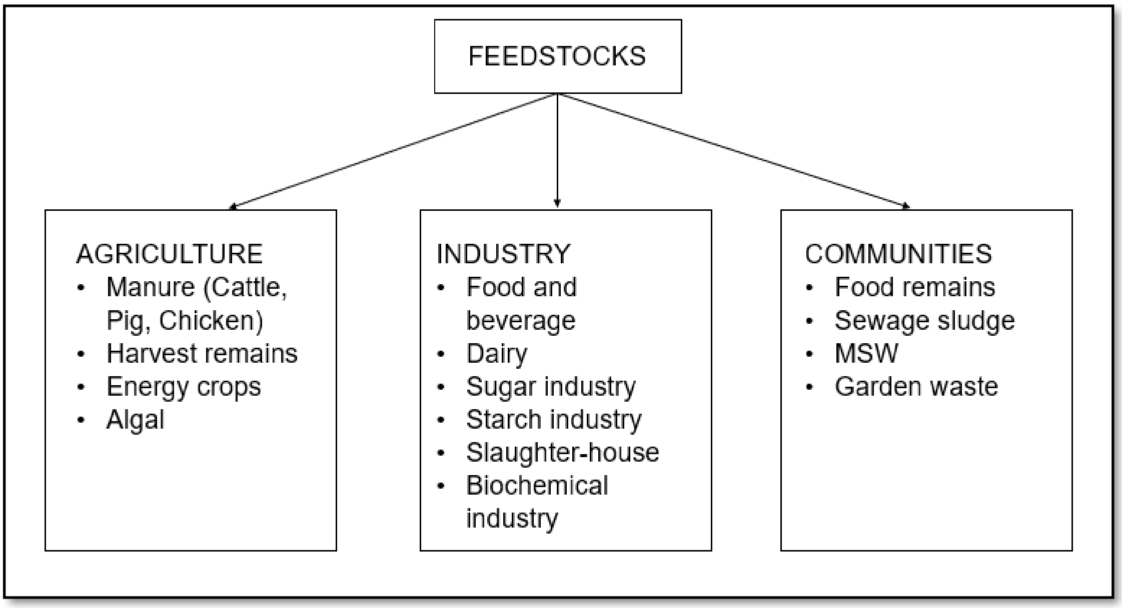


Figure 3. 2:Feedstocks available for Anaerobic digestion process

3.4. Anaerobic technology development

More than 50 million biogas systems have been globally implemented with the purpose of generating gas for cooking applications (Ilo *et al.*, 2021), (Tagne *et al.*, 2021). A significant proportion of African nations exhibited limited progress in technological advancements and a suboptimal approach in promoting the adoption of domestic biogas systems. In Africa, there exists a significant historical background pertaining to the utilization and investigation of household biogas digesters. Although not as prevalent as in Europe and Asia, the implementation of household anaerobic digesters in South Africa and Kenya dates to the 1950s. Similarly, these digesters have been introduced at different points in various countries in SSA, such as Ethiopia in 1957, Tanzania in the 1970s, and South Sudan in 2001 (Tagne *et al.*, 2021) (Dahunsi, Fagbiele and Yusuf, 2020). Until now, biogas digesters have been installed in many other SSA countries (Tagne *et al.*, 2021). Small-scale anaerobic digesters using domestic and household animal wastes are the most often utilized anaerobic digester model in Africa. Most of the literature on biogas utilization in Africa covers its potential contribution to community interests, environmental protection, and economic advancement, as well as the hurdles for large-scale uptake of the technology (Dahunsi, Fagbiele and Yusuf, 2020).

Anaerobic digestion technology is viewed as one alternative for supplying clean and renewable technologies in Low to Middle Income Countries, with the potential to play a key role in addressing energy and environmental concerns (Ilo *et al.*, 2021) (Tagne *et al.*, 2021). This technology has the potential to significantly contribute to Africa's energy needs (Ilo *et al.*, 2021). One of the notable features of this technology is its straightforward installation requirements, particularly in rural developing communities. This system has the potential to generate sufficient energy for cooking and heating purposes and can also be scaled up for community-based or commercial biogas generation initiatives (Tagne *et al.*, 2021). In several countries in SSA, there has been a notable installation of digesters that employ various types of feedstocks. These feedstock options include animal manure, human wastes, crop residues, abattoir wastes, municipal and industrial wastes, as well as waste from commercial farms such as manure produced on chicken and dairy farms. However, the operational status of these entities is limited as a result of inadequate technological selection and a scarcity of technical skills and studies. To make informed design choices, it is imperative to consider various factors such as the energy requirements of the prospective biogas consumer, the availability of feedstock (including quantity, seasonal availability, and ease of collection of both substrate and water), the utilization of local building materials, and the prevailing environmental conditions. These factors serve as crucial indicators that should be considered when selecting an appropriate AD (Dahunsi, Fagbiele, and Yusuf, 2020). Despite the numerous potential advantages, the adoption of small-scale anaerobic digesters in Africa remains relatively limited in comparison to other low- and middle-income countries. In the context of SSA, the effective implementation of biogas technology as both an energy and economic strategy has thus far been limited (Ilo *et al.*, 2021). Currently, various national and international development programs and agencies have implemented anaerobic digesters in rural households in SSA at minimal or no cost. This initiative aims to promote the uptake of bio-digesters and acknowledge their advantages. By the end of 2016, the African Biogas Partnership Programme (ABPP) had successfully implemented a total of 57,000 biogas digesters across five African nations (Ethiopia, Burkina Faso, Tanzania, Kenya, and Uganda,) since the program began in 2009 and about 320,000 people have benefitted from the programs by June 2018 (Ilo *et al.*, 2021). The high initial investment expenses associated with the installation of conventional AD systems continue to pose a significant obstacle in impoverished rural regions, hindering the widespread adoption of this technology (W, 2009).

3.5 Anaerobic digestion literature

The study conducted by (Akbulut, 2012) centred on the techno-economic analysis of electricity and heat generation derived from a biogas plant at a farm scale. The aim of the study was to examine the economic performance of biogas plants using the net present value and analyze the concepts of energetic pay-back time. The research findings demonstrated an annual electricity production of 2,223,951 kilowatt-hours (kWh) through the digestion of the feedstock. The amount of electricity produced per hour was 277.99 kilowatt-hours. The annual producible heat energy has been recorded as 2,566,098 kilowatt-hours (kWh), while the daily producible heat energy stands at 320.76 kWh. The economic viability of the plant, which includes dairy cows and stalls, was determined to be favorable, with a payback period of 3.4 years. This investment yielded profits and exhibited a positive net present value of V27.74 million. The implementation of the co-generation system has resulted in a significant annual reduction of 7506 metric tonnes of carbon dioxide (CO2) emissions.

(Tan *et al.*, 2021) performed a techno-economic evaluation of a farm biogas system that employed an anaerobic reactor. The experimental setup involved utilizing cow manure obtained from a dairy farm as the primary feedstock substrate. The quantity of cow manure generated daily ranged between 45 and 55 liters per day per cow, with a total of 200 milking cows contributing to this flow rate. Their findings revealed that under specific conditions, namely a temperature of 37 degrees Celsius and a hydraulic retention time (HRT) of 20 days, the biogas yield amounted to 934.54 mL/gVS. Consequently, this yielded a daily biogas volume of 11.28 m^3 and facilitated electricity generation of 22.56 kWh. In addition to the investigation, an economic evaluation was conducted, which unveiled that at a cow manure production rate of 55 L/day/cow, the net present value amounted to RM 611,936.09. In its entirety, the research showcased the practicality of employing a farm biogas system that utilizes cow manure as a feedstock, as evidenced by its substantial biogas generation and favorable economic outcome.

(Hanisah and Ibrahim, 2019) conducted a study wherein they developed a model for an AD process using Aspen Plus software. The objective of the model was to generate biogas from food waste. The study primarily examined the influence of hydraulic retention time (HRT) and food composition on methane production within the biogas system. The extension of hydraulic retention time (HRT) resulted in enhanced system stability, although at the expense of reduced methane composition. Conversely, shorter HRTs were found to be associated with elevated methane content. This study highlights the importance of HRT and the composition of food waste in maximizing the production of biogas from food waste using the AD process.

3.6 Software used.

3.6.1 HOMER Pro Software

HOMER Pro software is used in the present study to model a hybrid microgrid system. HOMER (Hybrid Optimization of Multiple Electric Renewables) is a microgrid software that addresses the challenges of creating an affordable microgrid system design for both off-grid and grid-connected modes (Çetinbaş, Tamyürek and Demirtaş, 2019). This is a computer simulation program created by the National Renewable Energy Laboratory in the United States (Singh, Baredar, and Gupta, 2015). It employs various renewable resources and components to craft system designs. Its key functions include simulating, optimizing, and conducting sensitivity analysis (Çetinbaş, Tamyürek and Demirtaş, 2019). During the simulation phase, this software calculates the lifetime expenses and assesses the viability of the proposed power system.

HOMER has the capability to model various power setups, including combinations of PV arrays, generators, wind turbines, run-off-river hydro turbines, and battery banks. It can simulate both off-grid and grid-connected systems that cater to electrical and thermal energy needs. During the optimization phase, it identifies the most economical approach to fulfill the electricity demand (Singh, Baredar, and Gupta, 2015). HOMER also offers the capability to perform sensitivity analysis, which assesses how uncertainties or modifications in variables affect the outcome. It reruns the optimization process for each variable under consideration. Given the diverse technical setups, fluctuations in component and fuel expenses, and resource availability, choosing the most efficient and feasible system can be challenging. Nevertheless, HOMER's optimization and sensitivity analysis algorithms simplify the task of pinpointing and assessing the ideal system (Hasan, 2019).

3.6.2 MATLAB Software

MATLAB is used for the present study to model a biogas digester system. MATLAB is an acronym that stands for Matrix Laboratory. MATLAB stands as a high-performance programming language employed in technical computation. It merges computation, visualization, and a coding environment into one. Additionally, MATLAB serves as a contemporary programming language environment, equipped with advanced data structures, integrated editing and debugging tools, and support for object-oriented programming. MATLAB proves to be an excellent tool for educational and research purposes. Notably, MATLAB operates as an interactive system that employs arrays as its primary data element, eliminating the need for dimensioning (Language and Computing, 2004), (Houcque, 2005).

Starting from 1984, this software program has been available for commercial use and has since become a widely adopted tool in numerous educational institutions and businesses globally. It features advanced built-in functions that facilitate a broad spectrum of calculations and incorporates user-friendly graphics commands for immediate result visualization. Specialized applications are categorized into toolbox packages, with toolkits available for signal processing, symbolic computation, control theory, and various other subjects (Houcque, 2005), (Hunt *et al.*, 2006).

3.7 Study Area Setting

3.7.1 Limpopo (Madombidzha village)

Limpopo Province, situated in the northeast of South Africa, plays a significant role in the national and regional economies of Southern Africa. Limpopo shares national borders with the provinces of Mpumalanga, Gauteng, and Northwest, and international borders with Botswana, Zimbabwe, and Mozambique (Goss, 2022). The province is composed of twenty-two Local

Municipalities organized into five Districts, namely, Capricorn, Mopani, Sekhukhune, Vhembe, and Waterberg (Goss, 2022), (Municipality and Plan, 2017). Figure 3.3 shows an overview of the districts with their municipalities. The study was conducted in Makhado Municipality, Vhembe district of Limpopo Province in South Africa. Makhado municipality has a population of 416 728 with 116 371 number of households (Municipality and Plan, 2017). The study was conducted at Madombidzha village outside Louis Trichardt with a population of 5500 and 1400 households.

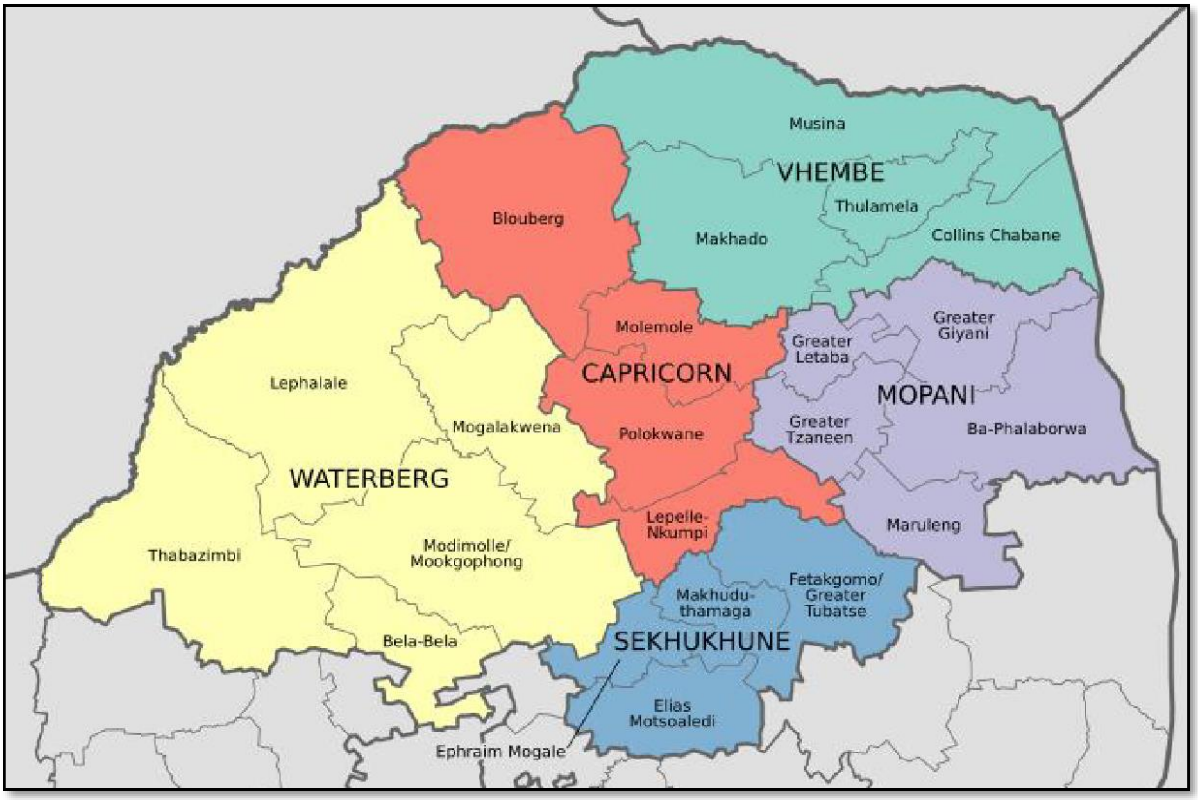


Figure 3. 3 Limpopo province districts

(Municipality and Plan, 2017)

3.7.1 Western Cape (Wallacedene Area)

Wallacedene is a small rural locality situated approximately 14 kilometers away from Bellville in the Western Cape region. Wallacedene originated as an informal housing settlement situated in the northeastern suburb of Cape Town, embodying the principles of Ubuntu. Communities of individuals experiencing homelessness congregated and established a communal settlement at an abandoned farm known as Uitkyk in Kraaifontein. These initial informal inhabitants gradually formed a cohesive community over time. In 2004, Wallacedene was recorded to have a population of approximately 21,000 individuals. Over time, this area experienced growth and was able to accommodate a larger population of 36,583 people. This population consisted of more than 10,000 households, with a majority residing in tin shacks and other temporary structures. Most of these individuals faced unemployment and lived in poverty, while a significant number were without permanent residence (Sinden, 2022). Figure 3.4 shows the area of the Wallacedene settlement.

Figure 3. 4 Wallacedene area

(Sinden, 2022)

3.8 Conclusion

Anaerobic digestion is a biological process that, in the absence of oxygen, decomposes complex organic matter into simpler chemical components. This process produces biogas, which is mostly made up of methane and carbon dioxide, with trace amounts of hydrogen sulphide, ammonia, and other gases. Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four phases of anaerobic digestion. Animal manure, agricultural wastes, food waste, and wastewater sludge are all possible feedstock materials for biogas production. The type of biomass material utilized and its inherent chemical makeup influence biogas yield and composition.

In the next chapter, HOMER Pro and MATLAB software tools are utilized to model and optimize biomass to biogas and electric power conversion process. HOMER Pro is a microgrid simulation and optimization software for hybrid renewable energy systems, whereas MATLAB is a high-performance programming language used for technical computing and data visualization. Madombidzha village in Limpopo Province, South Africa, and the Wallacedene area in the Western Cape region, South Africa, were chosen as study areas for this research.

These areas were selected based on their relevance to the study objectives and the availability of anaerobic digestion feedstock.

CHAPTER FOUR

SYSTEM DESIGN AND RESULTS

4.1 Introduction

This chapter presents the modelling of biomass conversion systems. The chapter consists of biomass data collection, an anaerobic digester process, energy access demand for the selected villages, and the electric power generation unit.

4.2 Biomass Conversion System

The biomass conversion system considered in this study is outlined in Figure 4.1. The system begins with the selection of villages and ends with the simulation of electric power generation for the selected villages. For biomass data collection, three different approaches were followed and grouped as Case studies 1, 2 & 3. Case studies 1 and 2 focus on the utilization of food and poultry wastes from Madombidzha village, while Case study 3 focuses on food waste from Wallacedene village. The anaerobic digester simulation was conducted for all three case studies to convert biomass to biogas. To model the electric power needed in the selected villages, an energy demand assessment was initially performed to estimate the amount of energy required by households. Subsequently, the biomass to electric power simulation was conducted for all three case studies using Homer Pro software.

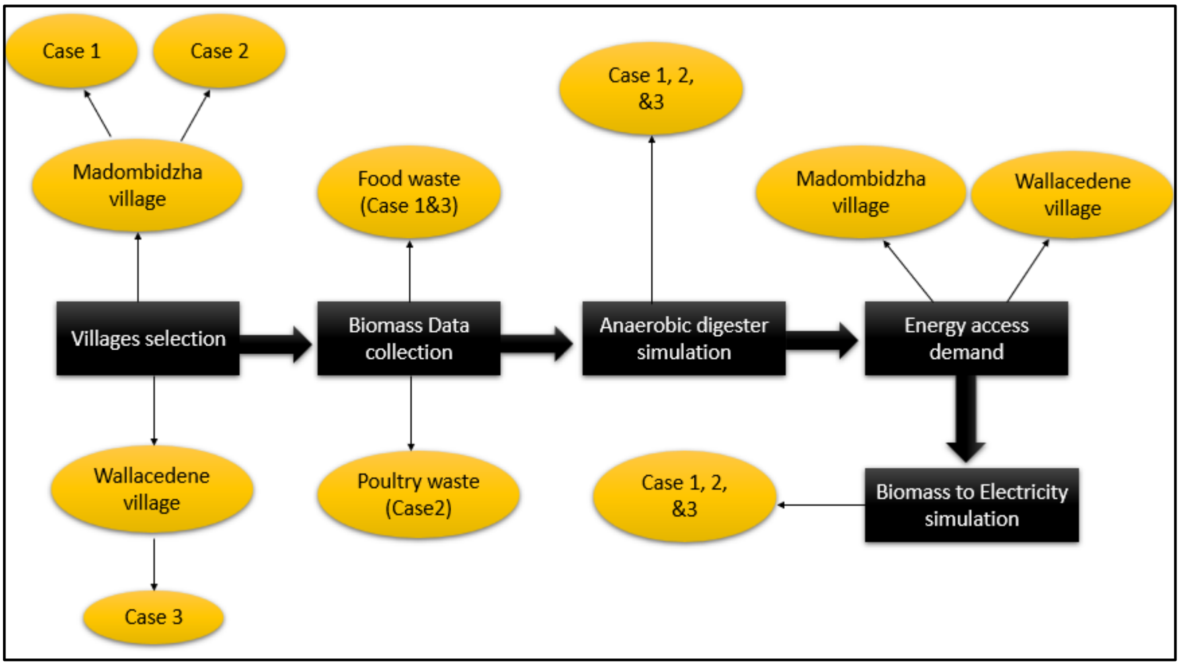


Figure 4. 1 The flow diagram showing the conversion of biomass from different villages into electric power.

4.3 Data collection

This section focuses on the process of collecting biomass data from two specific villages. It likely involves gathering information on the types and quantities of biomass available in these communities. The data collected included the biomass sources, such as food waste and poultry waste. This data was collected from randomly selected households as well as from other studies that were relevant to this research. Specifically, data were gathered from two different villages: Madombidzha village and Wallacedene village.

In Madombidzha village, the data collection process involved visiting a few houses, asking questions, and taking pictures. Interviews or surveys were conducted with the household owners to gather information. The questions asked during the interviews included the types of food bought by the households, the foods that were most frequently wasted, the amount of waste produced in a week, and the methods used by the households to discard their waste. On the other hand, for Wallacedene village, a previous study conducted by (Sinden, 2022) was used. (Sinden, 2022) study focused on the method of discarding food waste and the amount of food waste typically discarded by the community. The findings and data from the (Sinden, 2022) study was incorporated into this research.

4.3.1 Biomass Selection

The food wastes considered in this study are from Madombidzha and Wallacedene villages (Case studies 1 and 3), while poultry wastes were selected from Madombidzha village (Case study 2) to determine the amount of biogas that can be generated and subsequently be converted to electric power.

- **Case study 1: Madombidzha**

The amount of waste produced in each household depends on the number of people. The information provided suggests that households with 3 or 4 members generate less than half a bucket of waste in a week, resulting in just under a 25-liter bucket of waste in a month. On the other hand, households with 3 to 8 members produce a 25-liter bucket of waste in two weeks and approximately 2 buckets of waste in a month, sometimes less.

Based on the information received from different household owners, households have various methods of discarding their waste. Some households keep their waste in buckets as shown in Figures 4.3 and 4.4 and when the buckets get full, they take the waste to the nearest houses that have pigs. This suggests that the pig owners may use the organic waste as pig feed, which is a common practice in some areas.

Other households choose to dig a hole far from their house where they discard all their waste. A few households mentioned that they discard their waste outside the yard for dogs. It appears that in these cases, the waste serves as a food source for the local dogs. The types of food that are frequently wasted include pap, bread, fruits, and vegetables as shown in Figure 4.2. Other common types of wasted food mentioned were meat, eggs, milk, and rice. Additionally, Figure 4.4 shows collected rotten fallen fruits from one household that are being fed to pigs. The collected data were analyzed and transferred to MATLAB Homer Pro simulation for biogas and electric power production.

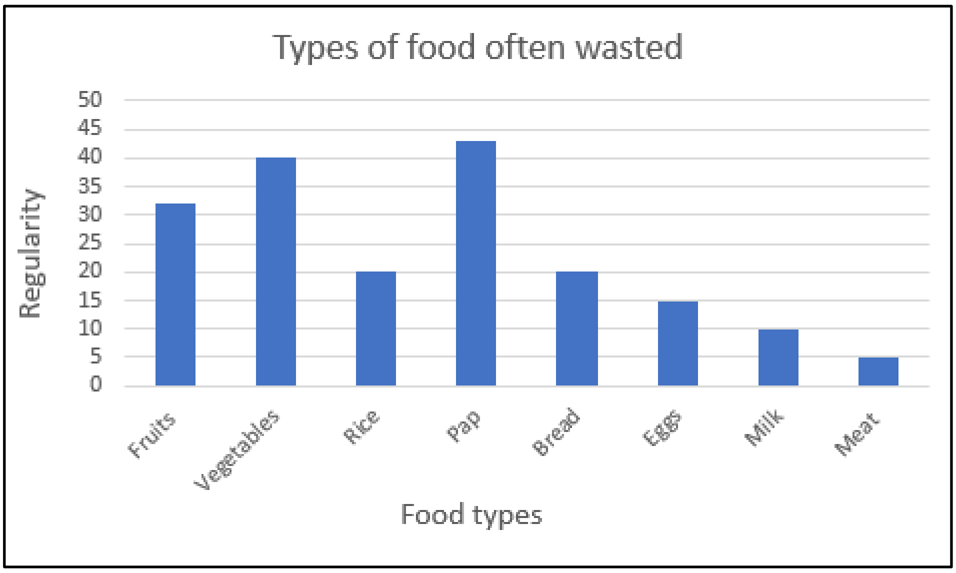


Figure 4. 2 Types of food mostly wasted in Madombidzha village.

Figure 4. 3 Food waste from Madombidzha village

Figure 4. 4 Fruits wastes from Madombidzha village

- **Case study 2: Madombidzha**

One house that has chickens was visited for a few questions. During the visit, the owner was asked about daily or weekly waste production. The chickens produce around 10 kg bags of waste every week and make almost 50 kg bags in a month. The wastes are used as a fertilizer when planting and some are discarded outside the yard far from houses.

Figure 4. 5 Madombidzha village poultry

Figure 4. 6 Poultry wastes from Madombidzha village.

- **Case study 3: Wallacedene food waste**

In this study, 63 households who were willing to participate, discussed their food-handling behaviour, the discarding of unwanted food, as well as their food waste patterns. The household's selection were based on the study conducted by (Sinden, 2022), which estimated that Wallacedene had a population of 21,000 people, most of whom lived in tin shacks and others in small houses like RDP. The analysis aimed to explore various aspects of food waste, including the categories of discarded food, disposal methods, waste sizes, environmental consequences, and the emotional impact on residents. Among the 42 respondents, comprising 74.12% from households with one, two, or three individuals responsible for food management, the predominant method of disposing of unwanted food was through garden compost and animal feed. In contrast, among the households with two individuals in charge of food management, only 18 respondents (21.17%) reported using waste bins, sewers, water drainage systems, or open fields to discard surplus food. The types of food waste commonly disposed of daily included leftovers such as meat bones, fats, rice, and samp. Many community members also noted that in Wallacedene, refrigerated food items and items left in the fridge often go to waste due to frequent electricity cuts, known as load shedding. This situation leads to the spoilage of various refrigerated items, including amasi, milk, and other perishable products. Figure 4.7 shows food that are being wasted more regularly.

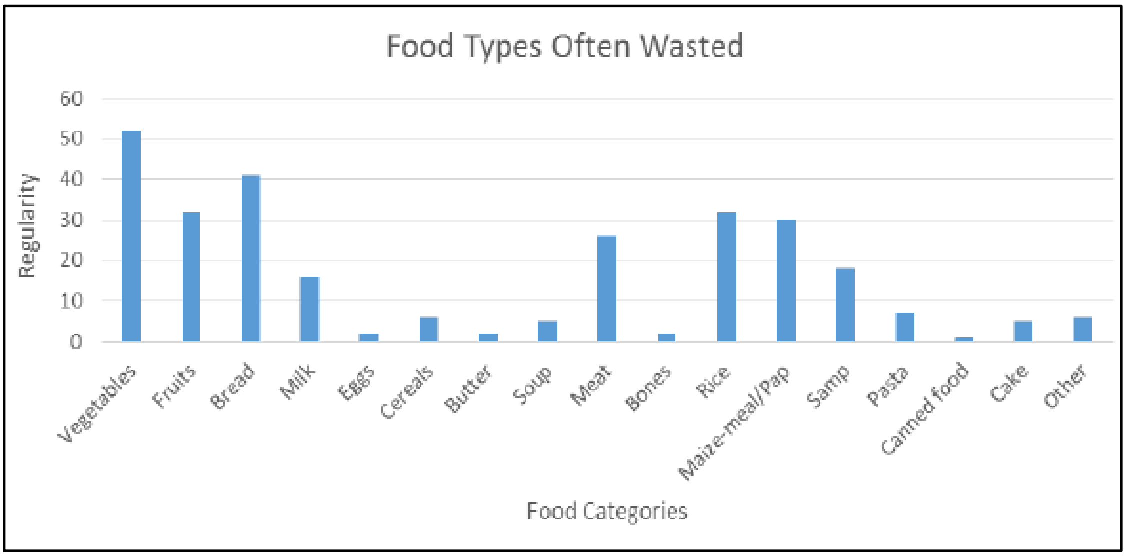


Figure 4. 7 Types of food often wasted by the Wallacedene community.

(Sinden, 2022)

4.4 Biomass modelling using an anaerobic system.

This section explores the modelling of anaerobic digesters based on the collected biomass data. It also assesses factors like biogas production potential, and digester design parameters.

4.4.1 Anaerobic digester simulation

For biogas simulation, food waste such as pap, rice, Samp, bread, vegetables, fruits, meat, and dairy food were taken into MATLAB to obtain the biogas volume for each respective food waste. The input parameters used during the anaerobic digester simulation are types of food waste, amount of waste, and percentage of the total solids for each feedstock type, as shown in Figures 4.8 (Case 1), 4.9 (Case 2) and 4.10 (Case 3).

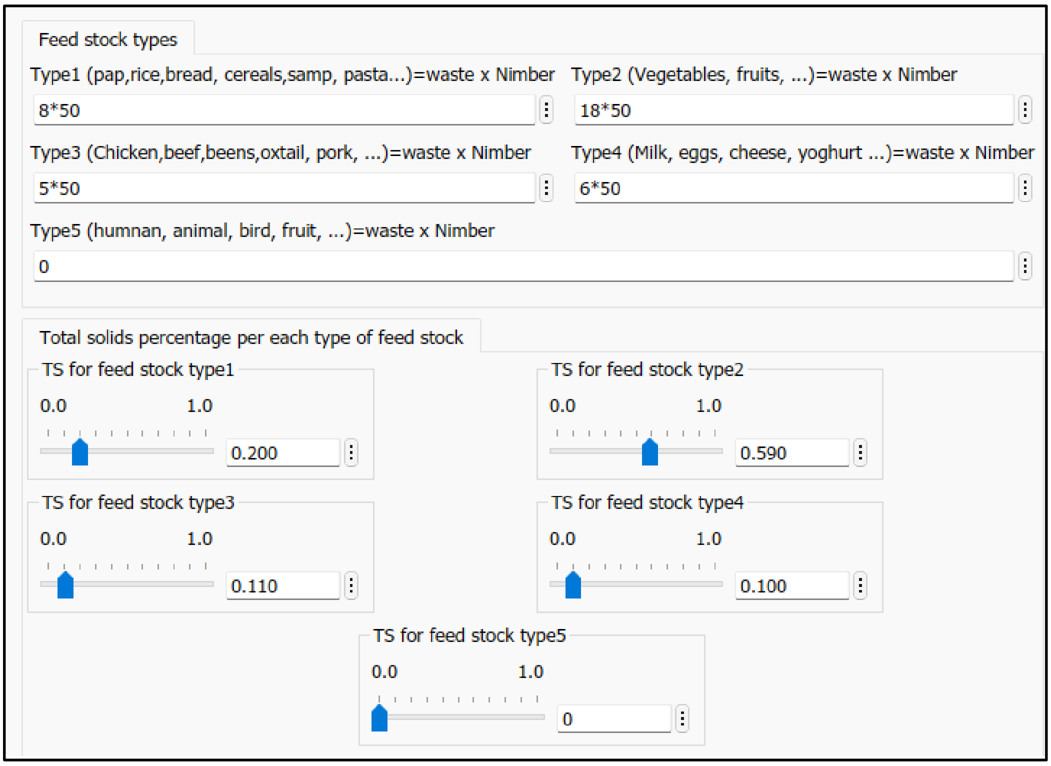


Figure 4. 8 Anaerobic digester design setup

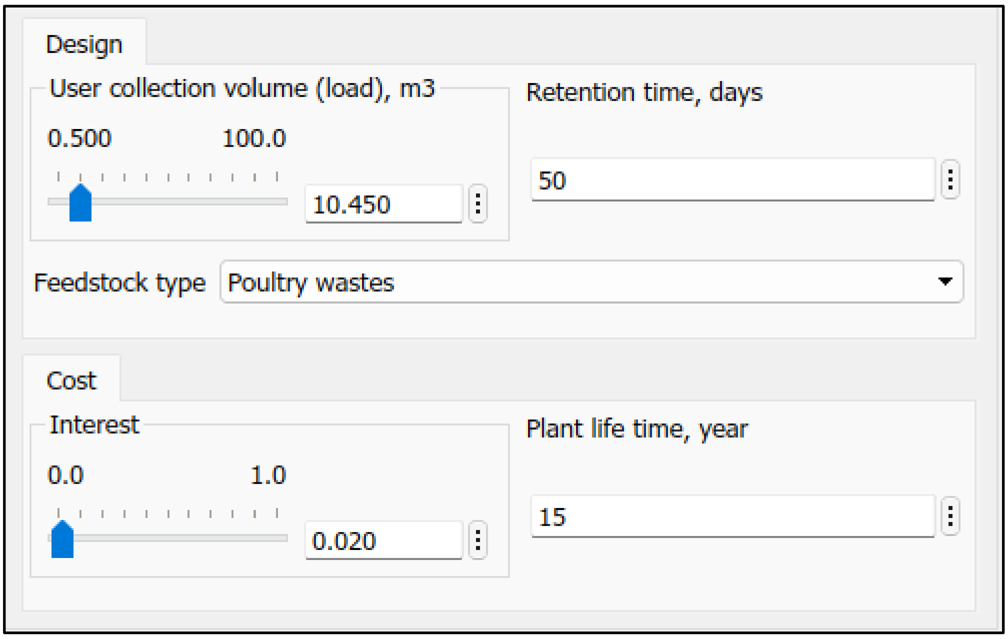


Figure 4. 9 Anaerobic digester design setup

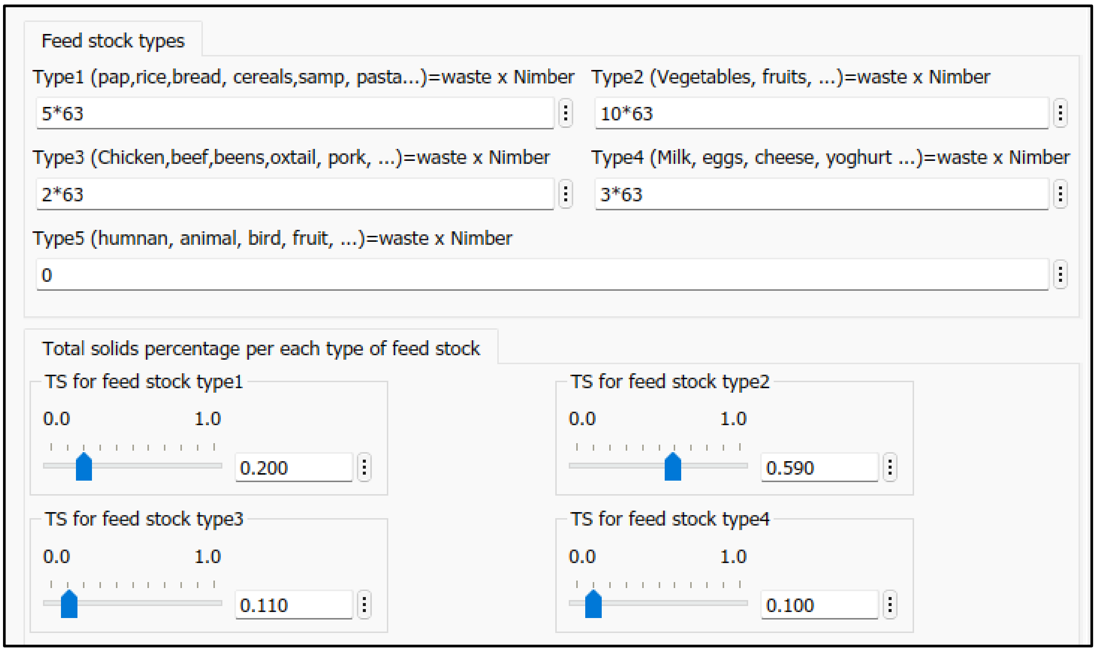


Figure 4. 10 Anaerobic digester design setup

The following sections present the different case studies investigated to convert biomass to biogas using the anaerobic digester.

- **Case study 1: Madombidzha village**

Figure 4.11 shows the outputs from a biogas anaerobic digester using food waste from Madombidzha village. On the left side of the diagram are the inputs from the digester setup (Figure 4.8). For methane production, solids waste needs to go through four stages, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. From Figure 4.11 and Table 1, the total volume of biogas produced was 522.3 m^3. The total solids waste of 668.5 kg was added to the digester. The amount of water added was 6506 kg to maintain the conditions for the anaerobic digestion process. The effective volume of the digester (working volume of digester) utilized for the anaerobic digestion process was 1772 m^3, and the total discharge (volume of liquid and solid by-products) that were removed from the digester was 1850 kg. The rest of the outputs are the digester design parameters.

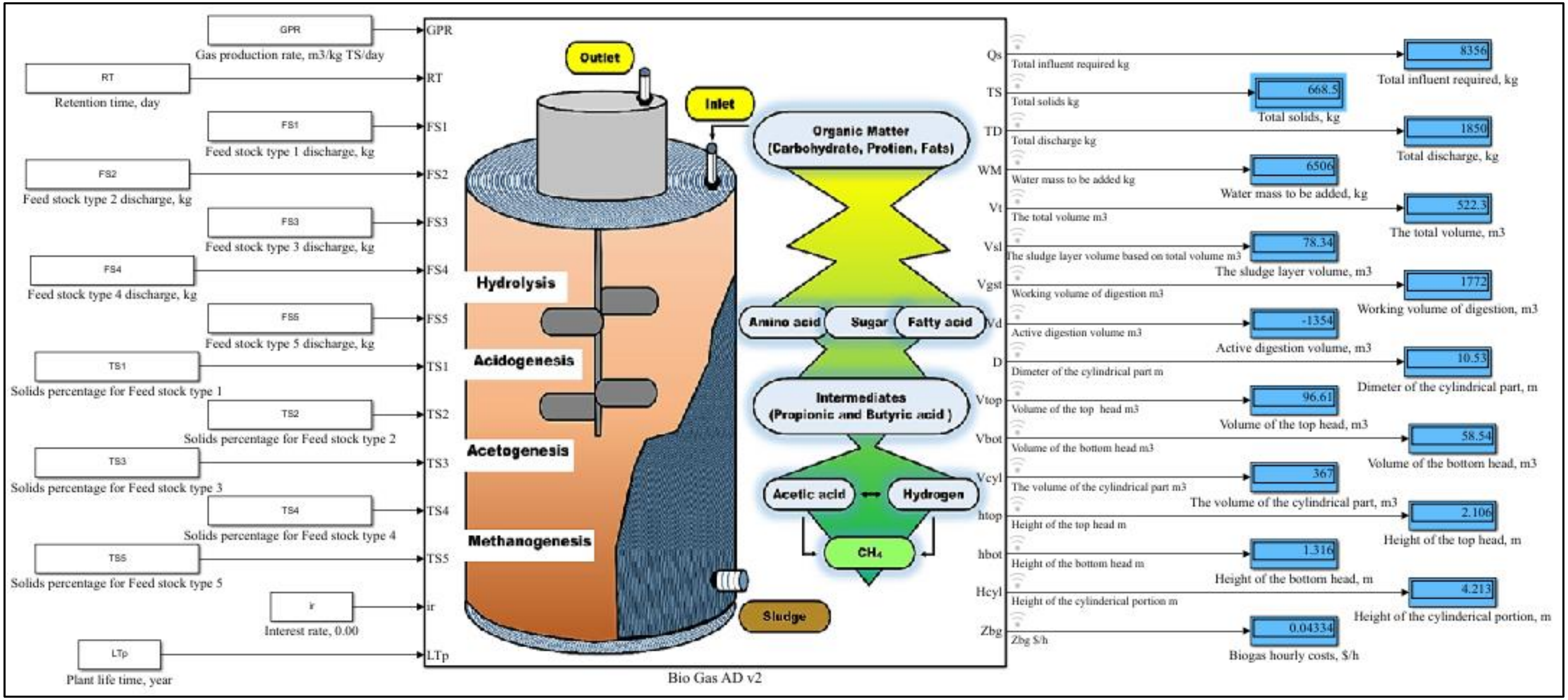


Figure 4. 11 Anaerobic digester system using food waste.

Table 4. 1 Anaerobic digester outputs for case study 1

Results output	Amount
Total volume, m^3	522.3
Total solids, kg	668.5
Water mass, kg	6506
Working volume of digester, m^3	1772
Total discharge, kg	1850
Retention time, days	50

- **Case study 2: Madombidzha poultry waste**

Figure 4.13 shows a biogas anaerobic digester using poultry waste from Madombidzha village poultry waste. On the left side of the diagram are the inputs from the digester setup (Figure 4.9). For methane production, solids waste needs to go through four stages, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. From Figure 4.12 and Table 2, the total volume of biogas produced was 209 m^3. The total solids material of 418 kg was added to the digester. The amount of water added was 1672 kg to maintain the conditions for the anaerobic digestion process. The effective volume of the digester (working volume of digester) utilized for the anaerobic digestion process was 167.2 m^3, and the total discharge (volume of liquid and solid by-products) that were removed from the digester was 1672 kg. The other outputs are the digester design parameter.

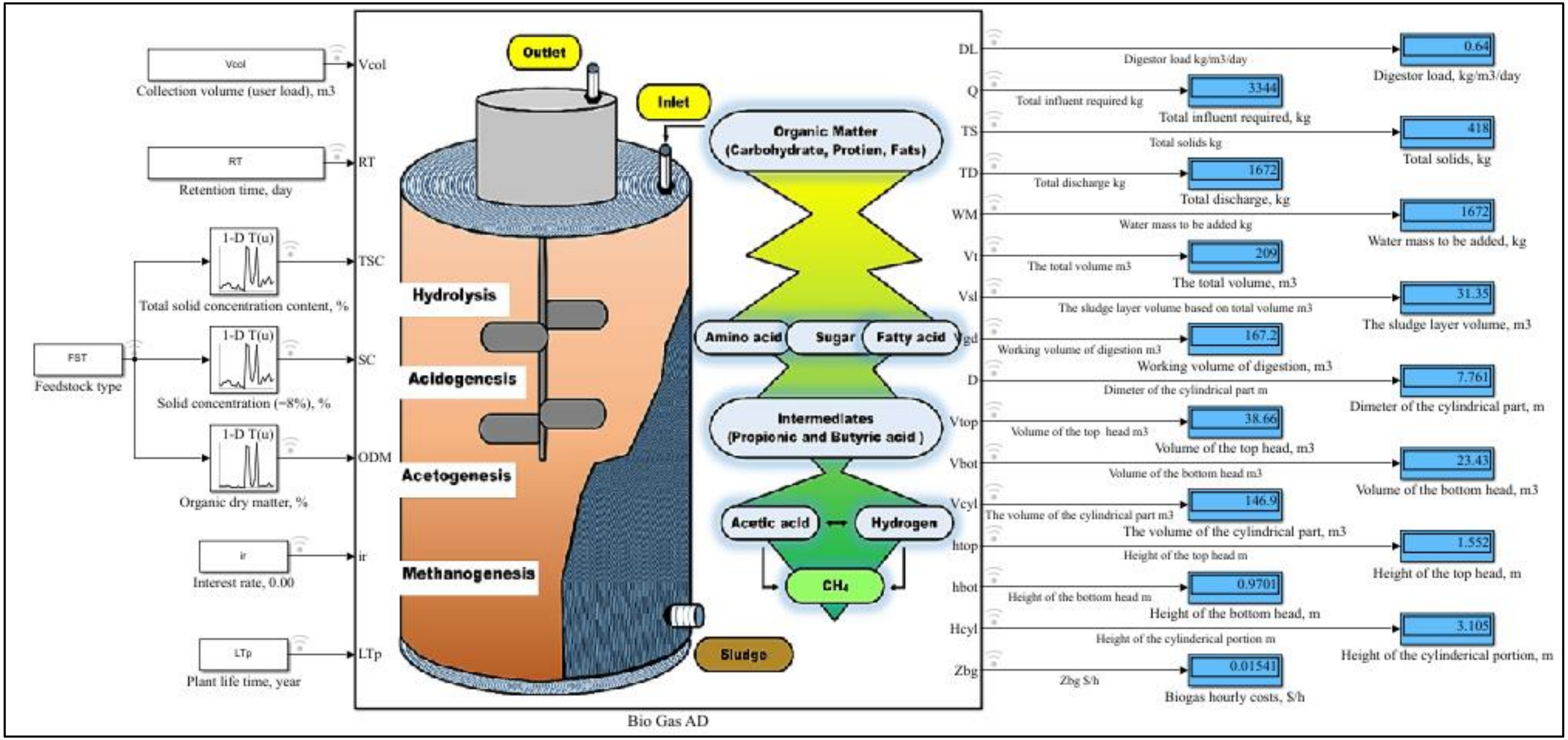


Figure 4. 12 Anaerobic digester using poultry waste

Table 4. 2 Anaerobic digester results for Case Study 2

Results output	**Amount**
Total volume, m^3	209
Total solids, kg	418
Water mass, kg	1672
Working volume of digester, m^3	167.2
Total discharge, kg	1672
Retention time, days	50

- **Case study 3: Wallacedene village**

Figure 4.13 shows the results of a biogas anaerobic digester using food waste from Wallacedene village. On the left side of the diagram are the inputs from the digester setup (Figure 4.10). For methane production, solids waste needs to go through four stages, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. From Figure 4.12 and Table 2, the total volume of biogas produced was 365.2 m^3. The total solids material of 467.5 kg was added to the digester. The amount of water added was 4583 kg to maintain the conditions for the anaerobic digestion process was added to the digester. The effective volume of the digester (working volume of digester) utilized for the anaerobic digestion process was 2267 m^3, and the total discharge (volume of liquid and solid by-products) that were removed from the digester was 1260 kg. The other outputs are the digester design parameter.

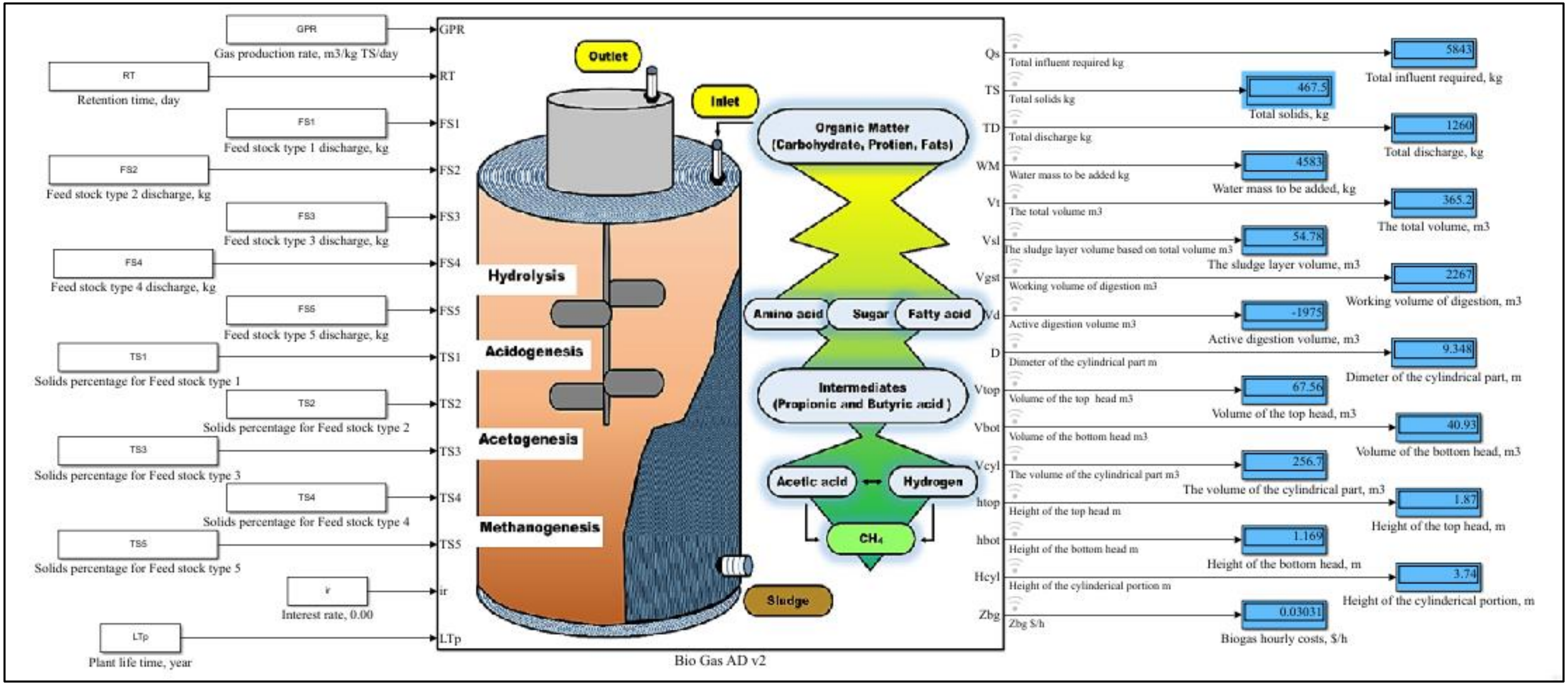


Figure 4. 13 Anaerobic digester system using food waste

Table 4. 3 Anaerobic digester results for Case Study 3

Results output	Amount
Total volume, m^3	365.2
Total solids, kg	467.5
Water mass, kg	4583
Working volume of digester, m^3	2267
Total discharge, kg	1260
Retention time, days	50

4.5 Energy Access Demand Assessment

This section focuses on the analysis of energy access demand within the two villages. It involves evaluating the current energy needs of the communities and assessing the energy consumption patterns. Understanding the energy access demand was crucial for designing appropriate solutions that could meet the energy requirements of the communities effectively.

- **Madombidzha village**

Energy access demand for Madombidzha village was done in order to get the amount of energy used by the whole village in a day. Electrical appliances used to estimate the energy demand were those that every house uses almost every day. The appliances include lights and a stove. The energy demand was calculated according to how much energy each appliance draws in a day while in use. Table 4.4 shows appliances and their wattage. The number of appliances in each house was classified from the poorest to richest households.

Table 4. 4 Households Appliances

Appliances	Energy consumption (kW)	Low Income households	Medium Income households	High Income households
Lights	0.028	3	8	12
Stove	1.2	1	1	1

In order to estimate the total amount of energy used in the village, the energy access demand method was used. It was assumed that there were low, medium, and high-income households in the village. Table 4.5 shows the amount of energy used in a 24-hour day for 50 households. From the 50 households chosen, it was assumed that 10 households were low-income, 20 were medium-income, and 20 were high-income. The total amount of energy was multiplied by the total number of households to get the total energy demand.

Table 4. 5 Household energy demand in a day

Hours	Low Income households	Medium Income households	High Income households
00:00	0,028	0,084	0,112
01:00	0,028	0,084	0,112
02:00	0,028	0,084	0,112
03:00	0,028	0,084	0,112
04:00	0,028	0,084	0,112
05:00	0,028	0,084	0,112
06:00 - 16:00	0	0	0
17:00	0	1,2	1,2
18:00	1,284	1,424	1,48
19:00	1,284	1,424	1,48
20:00	0,084	0,224	0,28
21:00	0,084	0,224	0,28
22:00	0,084	0,224	0,28
23:00	0,028	0,084	0,112
Total (kw)	**3,016**	**5,308**	**5,784**

- Low-income households: $3.016 \times 10 \ = 30.16kW$
- Medium-income households: $5.308 \times 20 \ = 106.16kW$
- High-income households: $5.786 \times 20 \ = 115.72kW$
- Total consumption: $30.16kW + 106.16 + 115.72 \ = 252.04kW/day$

- **Wallacedene village**

For Wallacedene, it was assumed that there are only low and medium households as most of the households fall under those categories. Energy demand was done using three appliances: Stove, lights, and fridges as shown in Table 4.6. The fridge was added as the community complained that their load-shedding can go on for over a week making them waste refrigerated food a lot.

Table 4. 6 Households Appliances

Appliances	Energy consumption (kW)	Low Income households	Medium Income households
Lights	0.028	3	8
Stove	1.2	1	1
Fridge	0.15	1	1

To estimate the total amount of energy used in the village, the energy access demand method was used. It was assumed that there were low and medium households in the village. Table 4.7 shows the amount of energy used in a 24-hour day. From the 63 households chosen, it was assumed that 30 households were low-income and 33 were medium income. The total amount of energy was multiplied by the total number of households to get the total energy demand.

Table 4. 7 Household energy demand in a 24-hour day

Hours	Low Income households	Medium Income households
00:00	0,178	0,234
01:00	0,178	0,234
02:00	0,178	0,234
03:00	0,178	0,234
04:00	0,178	0,234
05:00	0,178	0,234
06:00	0,15	0,15
07:00	0,15	0,15
08:00	0,15	0,15
09:00	0,15	0,15
10:00	0,15	0,15
11:00	0,15	0,15
12:00	0,15	0,15
13:00	0,15	0,15
14:00	0,15	0,15
15:00	0,15	0,15
16:00	0,15	0,15
17:00	0,15	1,2
18:00	1,434	1,424
19:00	1,434	1,424
20:00	0,234	0,224
21:00	0,234	0,224

22:00	0,234	0,224
23:00	0,178	0,084
Total (kW)	**6,616**	**7,858**

- Low-income households: $6.616 \times 30 \ = 198.48kW$
- Medium-income households: $7.858 \times 33 \ = 259.31kW$
- Total consumption: $198.48kW + 259.31 \ = 457.79kW/day$

4.6 Biomass to Electric Power Conversion System.

Biomass data from case studies 1, 2, and 3 were used in a hybrid microgrid system for electric power production. Each case study was simulated separately. In all the cases the system design included a generic 500kw biogas generator, a generic lithium-ion 3000kwh storage battery, a converter, and electric loads.

4.6.1 Case studies 1 & 2 (Madombidzha village)

- **Daily Load Profile**

The load profile of Madombidzha village was determined using three categories of households (low, medium, and high income). Figure 4.14 shows the amount of energy required by the loads in a day. In this figure, most energy is required from half past five in the afternoons to half past eight in the evenings, as many house owners should be using stoves at that time, especially in medium and high-income households. Whereas for the rest of the hours, only light bulbs were used. During the day, energy usage is minimal as most people are at work or school. The microgrid for Madombidzha village required 252 kWh/day with a peak of 127 kW.

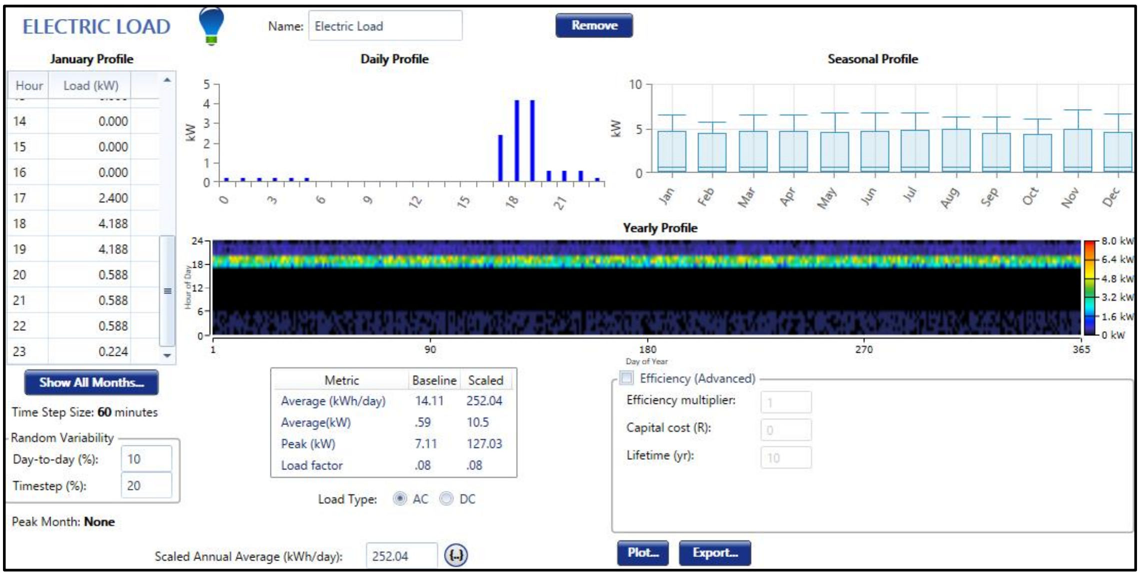


Figure 4. 14 Madombidzha village load profile

- **Design of hybrid microgrid system**

Figure 4.15 show the schematic diagram of a hybrid microgrid structure in which the loads are connected to the AC bus. The biogas generator is also connected to the AC bus while the energy storage battery is connected to a DC bus. A bidirectional power converter ties the DC bus to the AC bus for bidirectional energy transfer.

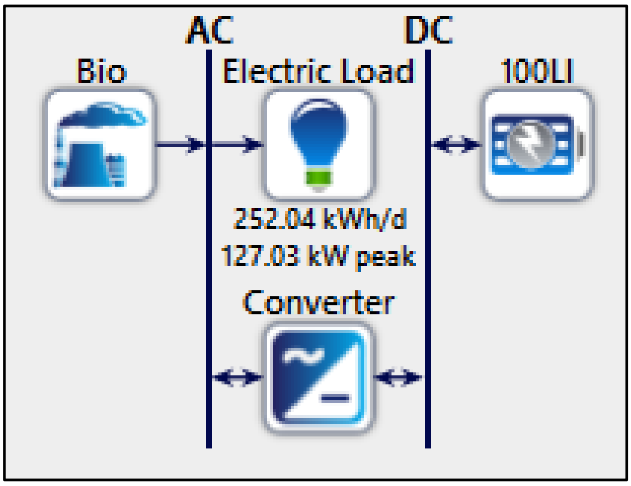
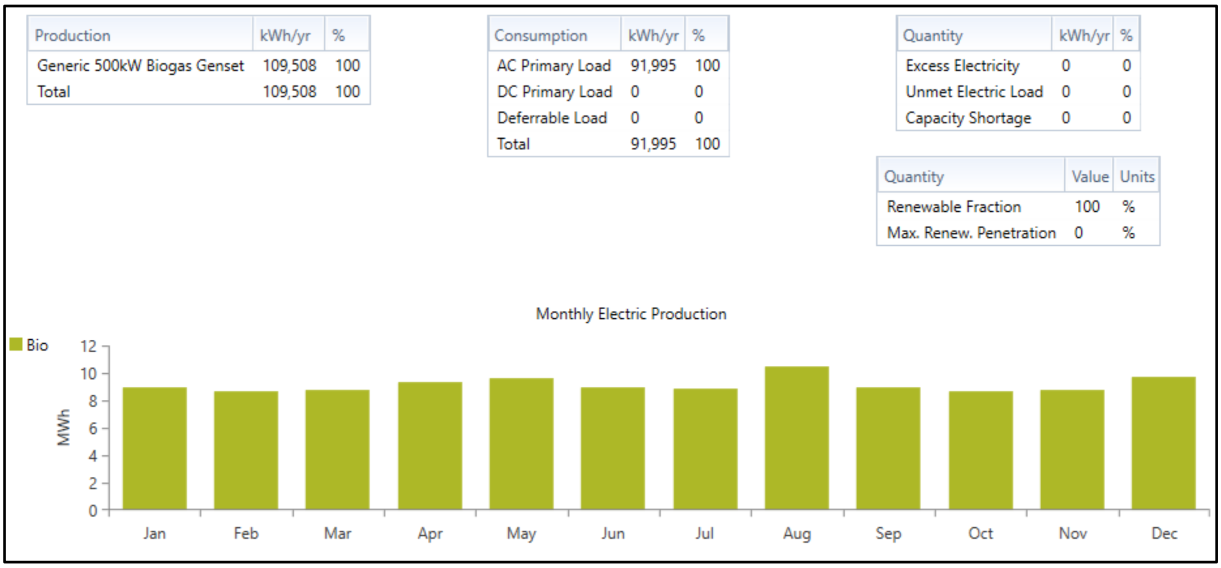


Figure 4. 15 Schematic design

- **Electricity Production**

The electricity production each month from biomass in the Madombidzha village was between 8MWh and 10MWh, as shown on Figure 4.16. The total electricity produced per year was 109,508kWh/ year with a consumption of 91,995kWh/ year. The generator used was a 500kW biogas generator consuming about 335 tons per year of fuel, operating for 381 hours per year.



Production	kWh/yr	%
Generic 500kW Biogas Genset	109,508	100
Total	109,508	100

Consumption	kWh/yr	%
AC Primary Load	91,995	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	91,995	100

Quantity	kWh/yr	%
Excess Electricity	0	0
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	0	%

Figure 4. 16 Electric power production

From poultry waste in Madombidzha village the electricity production of each month was between 7.8MWh and 9MWh monthly as shown on figure 4.17. The total electricity produced per year was 109,400kW/ year with a consumption of 91,995kW/ year. The generator used was a 500kW biogas which was consuming 342 tons/year of fuel. It was operating for 412 hours per year.

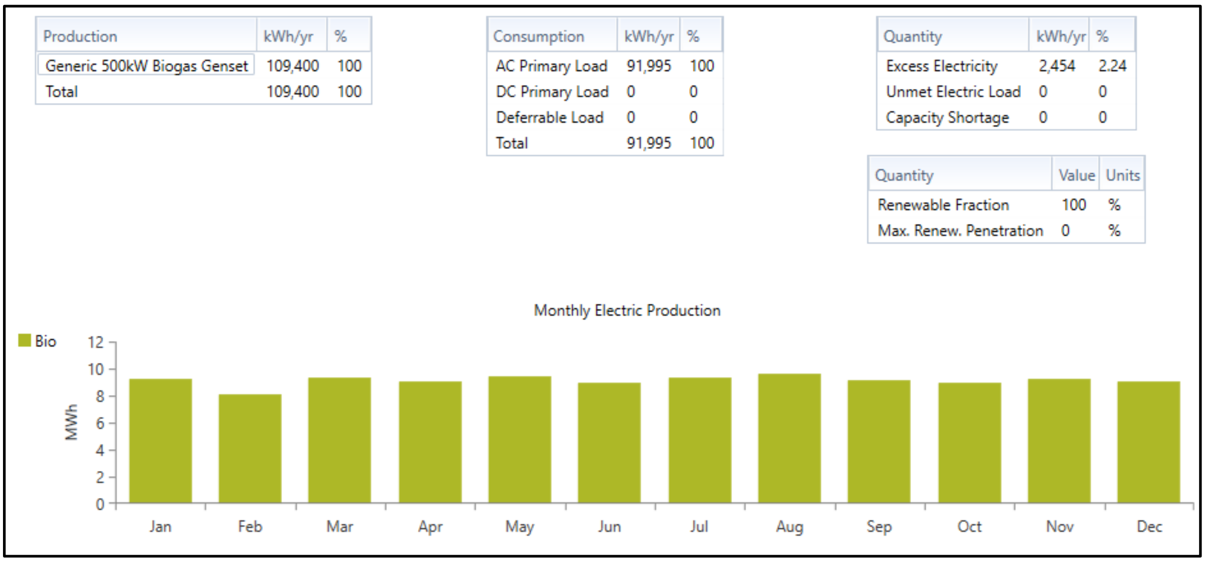


Figure 4. 17 Monthly Electric power production

4.6.2 Case study 3 (Wallacedene)

- **Daily Load Profile**

The system is designed to supply lights, fridge and stoves. Three categories of households were used to determine the load profile. The categories used were low income, and medium income households. Figure 4.18 shows the amount of energy required by the loads in a 24h day which is 457.79kWh/day. As shown the figure most energy is required from half past five afternoons to half past eight as many houses should be using stoves at that time especially in medium income and high-income households. The rest of the hours the system was used for fridge and lights. During the day the system was only used for fridges as most people were at work or school.

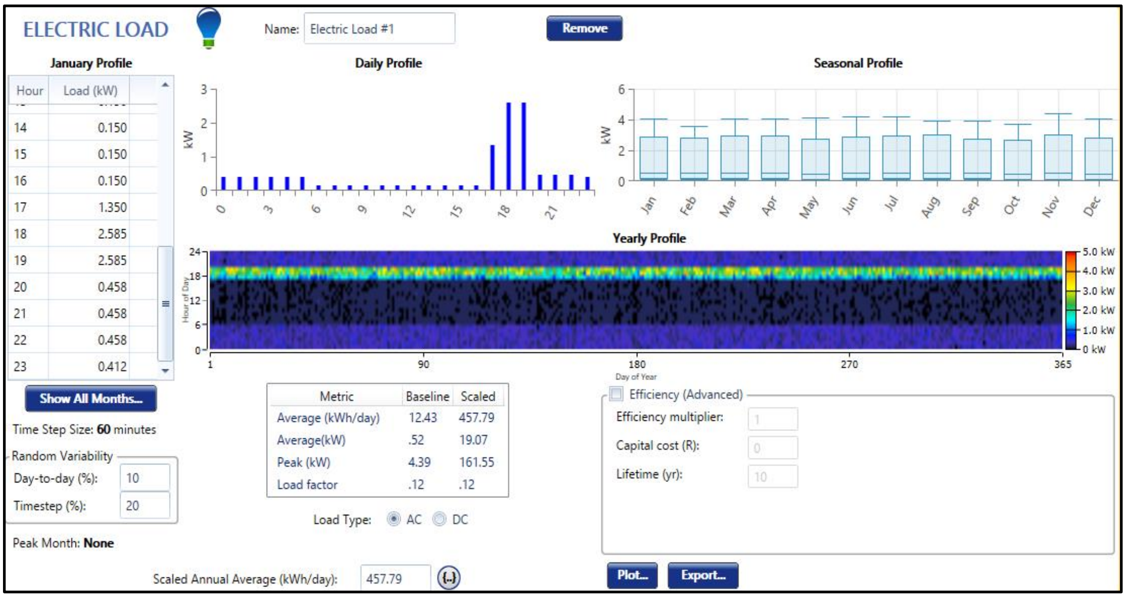


Figure 4. 18 Wallacedene load profile

- **Design of Hybrid Microgrid**

In this hybrid microgrid structure, the loads are connected to the AC bus as shown on Figure 4.19. The biogas generator is also connected to the AC bus and energy storage battery is connected to a DC bus. A bidirectional power converter ties the DC bus to the AC bus for bidirectional energy transfer. The microgrid for Wallacedene village required 457.79 kWh/day and has a peak of 142.61 kW.

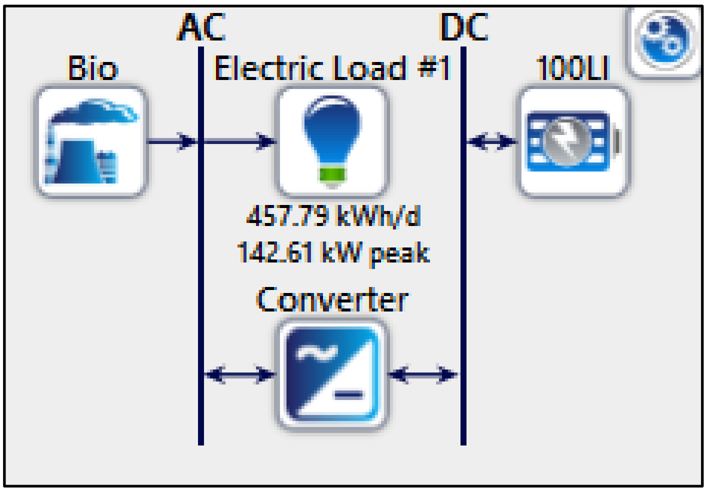


Figure 4. 19 Schematic design

- **Electricity Production**

The electricity production of each month was between 14MWh and 18MWh monthly as shown on figure 4.20. The total energy production is 202,777kWh/year. The generator is operating for 796 hours per year and consuming 625 tons of fuel per year. The consumption was

167,193kWh/ year which is lower than the production. There were no unmet electric loads and shortage of electricity.

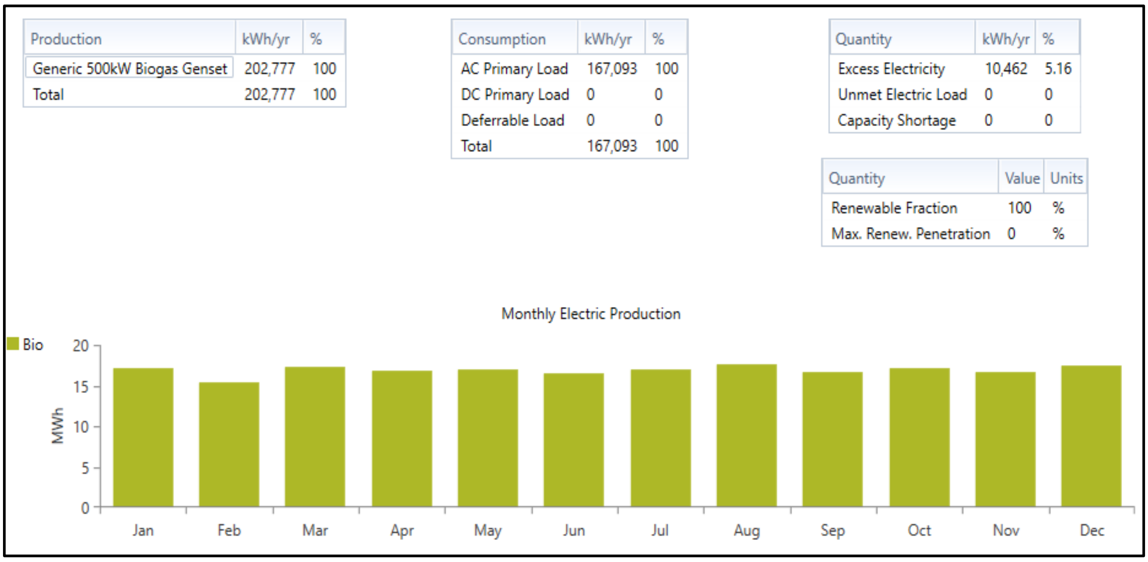


Figure 4. 20 Electric power production

4.7 Results

4.7.1 Anaerobic system

The results of the anaerobic digester system are shown on table 4.8. For case 1, a biogas volume of 522.3 m^3 was produced from food waste biomass, while in case 2, a biogas volume of 209 m^3 was produced from poultry waste. Case 3 produces a volume of 365.2 m^3 from food waste.

Table 4. 8 Anaerobic digester results

	Madombidzha Food waste (Case1)	**Madombidzha Poultry food (Case 2)**	**Wallacedene Food waste (Case 3)**
Biomass available (Kg/ month)	668.5	418	467.5
Biogas production (m^3/50 days)	522.3	209	365.2
Retention time (days)	50	50	50

4.7.2 Hybrid microgrid system

Table 4.9 shows the electric power required and generated from hybrid microgrid system for the three cases using Homer Pro software. Cases 1 and 2 require energy demand of 252.04kwh/ day. From the biogas generator, the hybrid microgrid system was able to produce about 107.710 kwh/ year and 109.400 kwh/ year, respectively. Case 3 require energy demand of 457.79 kWh/day and the system produced about 199.000kwh/year. The energy consumption per year from case 1,2, and 3 was 91.995, 91995 and 167.057 kWh/year, respectively.

Table 4. 9 Electric power required and generated from hybrid microgrid system.

	Madombidzha Case 1	**Madombidzha Case 2**	**Wallacedene Case3**
Biomass available (Kg/ month)	668.5	418	467.5
Energy demand (kwh/day)	252,04	252,04	457,79
Electricity production (kwh/yr.)	109,508	109,400	199,000
Electric power consumption (kwh/yr.)	91,995	91,995	167,051

4.7.3 Hybrid Microgrid Cost

Table 4.10 illustrate the cost of the hybrid microgrid system for the three case studies. The initial cost for the hybrid microgrid system for three case studies were R2.31 million for case 2, R1.77 million for case 2, and R1.91 million for case 3. The net cost was R2,75 million, R2,04 million, and R2,44 million, with operating costs of R30,130, R18.430 and R41,200, respectively. The maintenance costs for the hybrid microgrid are R30,130, R18,430, and R41,200 for cases 1, 2 and 3, respectively. The years of operation for each hybrid microgrid were 32 for case 1, 48 for case 2 and 27 for case 3.

Table 4. 10 Hybrid Microgrid System Cost

	Case 1	Case 2	Case 3
Capital cost	R2.31M	R1.77M	R1.91M
Net present cost	R2,75M	R2.04M	R2,44M
Operating cost	R30,130	R18.430	R41.200
Maintenance cost	R30,130	R18,430	R41,200
Operational life (years)	32	48	27

4.7.4 Discussion

The present investigation incorporates two simulation models, namely the anaerobic digestion and the power generating systems. The results obtained from this study indicate that employing an anaerobic digestion system for processing kitchen and animal waste presents a viable option for biogas production. The biogas generated from food and poultry wastes were obtained from rural areas. The results indicate a positive correlation between the duration of waste retention within the digester and the quantity of biogas produced. Furthermore, the results analysis reveals that long HRT produced a high volume of biogas while less HRT produced less volume. The HRT for all the three cases was 50 days maximum. Poultry wastes weighing 418 kg generated a biogas volume of about 209 m^3, while 668.5 kg of food waste produced a volume of about 522 m^3. The resulting biogas can be utilized either as a cooking fuel or converted into electric power.

An evaluation of energy demand was conducted for two villages, namely Madombidzha (case studies 1 and 2) and Wallacede (case study 3). For case studies 1 and 2, the daily energy demand was calculated as 252.04 kWh, while for case study 3, the daily energy demand amounts to 457.79 kWh. The energy production from Figures 4.16, 4.17, and 4.20 from the hybrid microgrid system for case studies 1, 2, and 3 were determined as 109,508 kWh/year, 109,400 kWh/year, and 199,000 kWh/year, respectively. Considering the energy requirements, the electric power generated by the hybrid microgrid system satisfactorily met the demands of the two villages, although the energy was covering few appliances.

Comparing with previous studies (as discussed on chapter 3), (Akbulut, 2012) demonstrated an annual electricity production of 2,223,951 kWh through the digestion of the cow's feedstock. The economic viability of the plant (includes dairy cows and stalls) was determined to be favourable, with a payback period of 3.4 years. This investment yielded profits and exhibited a positive net present cost (NPC) of V27.74 million. Whereas in this study electric power production was 199.000 kWh/year using food waste. The NPC value was R2.44million

(Tan *et al.*, 2021) performed a study for cow manures that were generated daily and ranged between 45 and 55 litres per day. The total of 200 milking cows contributed to this flow rate. Their findings revealed that under specific conditions, namely a temperature of 37 degrees Celsius and HRT of 20 days, the biogas yield amounted to 934.54 mL/gVS. Consequently, this yielded a daily biogas volume of 11.28 m^3 and facilitated electricity generation of 22.56 kWh. In addition, an economic evaluation was conducted, which unveiled that at a cow manure production rate of 55 L/day/cow, amounted to NPC of R611,936. To compare with the present study, chicken wastes were used to produce biogas and electric power. A total of around eight chickens generated 10 kg of waste every week produced a biogas volume of about 209 m^3, with an HRT of 50 days.

(Hanisah and Ibrahim, 2019) conducted a study wherein they developed a model for an AD process using Aspen Plus software. The study primarily examined the influence of HRT and food composition on methane production within the biogas system. The extension of HRT resulted in enhanced system stability, although at the expense of reduced methane composition. Conversely, shorter HRTs were found to be associated with elevated methane content. This study highlights the importance of HRT and the composition of food waste in maximising the production of biogas from food waste using AD process. Although in this study, it was found that longer HRT allows the digester to produce more biogas. Whereas less biogas was produced during shorter HRT.

CHAPTER FIVE
SUMMARY OF THE CHAPTERS

5.1 Conclusion

This study has investigated the feasibility of converting household and poultry waste from rural areas in Limpopo and Western Cape province, South Africa, into biogas for cooking, and lighting. The study employed two simulation models, one for the anaerobic digestion process and another for the subsequent power generation. The anaerobic digester was used to convert biomass into biogas for cooking while the hybrid microgrid system employed biomass to generate electric power. Furthermore, MATLAB software was used for the anaerobic digestion method while HOMER software was used to model the hybrid microgrid system. A detailed analysis of the techno-economic aspects of the hybrid microgrid system to determine if it is financially feasible and practical was also conducted. The outcome of the study has shown the potential of combined heat and power systems fuelled by biomass to address energy issues, enhance living conditions, and reduce environmental impact, which as a results could lead to sustainable energy solutions in African villages. Some of the key findings are presented as follows:

- Rural households in the surveyed areas generally produce just average amount of waste, primarily consisting of leftover, rotten fruits and vegetables from gardens and spoiled food from refrigerators.
- The anaerobic digester system demonstrated substantial efficacy, with approximately 600 Kg of food waste yielding an impressive biogas volume of approximately 500 m^3. Notably, the biogas produced from such waste quantities can sufficiently fuel cooking activities for an extended period. This observation suggests that the adoption of food waste digesters has the potential to enable rural households to transition away from traditional cooking methods involving open fires, thereby contributing to a reduction in greenhouse gas emissions.
- The hybrid microgrid system, operating on biomass derived from food waste, exhibited an annual energy production of approximately 199,000 kWh. Concurrently, the daily electric power demand was found to average 467.5 kWh. These findings highlight the potential of biogas generators to alleviate electricity-related challenges and financial burdens faced by individuals grappling with power outages in rural regions.
- The techno-economic evaluation of the hybrid microgrid system indicated an approximate cost of R2.5 million, encompassing installation, maintenance, and operational expenses.

5.2 Recommendations

As African villages endeavour to improve energy access and sustainability, the findings in this research has contributed valuable insights to the ongoing discourse on the adoption of renewable energy. In future studies, the analysis process, empower local communities should be refined so as to pave way for the successful deployment of low-cost biogas-fed combined heat and power systems. These systems have the potential to catalyse positive changes by providing African villagers with renewable energy, economic opportunities, and a higher quality of life. Several recommendations could be suggested to guide further research and practical applications:

For analysis, this research employs a combination of MATLAB and HOMER. Researchers might consider a more seamless integration of the two tools to improve the precision of their findings. This integration would enable a comprehensive evaluation of the entire biogas-fuelled combined heat and power system, considering both anaerobic digestion and electricity production in a single model.

Given the complexity of the techno-economic analysis, it is important to conduct sensitivity analyses. Moreover, future studies should investigate energy demand, system efficiency, and maintenance costs since there is a variation in critical parameters such as feedstock availability. This analysis will provide a deeper comprehension of the system's efficacy under various circumstances.

The successful implementation of biogas systems depends not only on technical factors, but also on community engagement and local capacity development. Future research should emphasise collaborating closely with local communities to develop awareness, knowledge, and skills regarding the operation and maintenance of the proposed systems.

BIBLIOGRAPHY/REFERENCES

Aboagye, B. *et al.* 2021. Status of renewable energy resources for electricity supply in Ghana. *Scientific African*, 11: e00660. https://doi.org/10.1016/j.sciaf.2020.e00660 [22 January 2022]

Agency, U. S. E. P. 2007. Biomass Combined Heat and Power Catalog of Technologies report. https://www.epa.gov/sites/default/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf [13 February 2022]

Akbulut, A. 2012. Techno-economic analysis of electricity and heat generation from farm-scale biogas plant. *Energy*, 44(1): 381–390. Doi: https://doi.org/10.1016/j.energy.2012.06.017 [25 March 2022]

Ali, A. and Stu, K. 2018. Kinetic Study of Kitchen Waste Anaerobic Digestion. unpublished master's Thesis, Shenyang Aerospace University. https://www.researchgate.net/publication/325988599_Kinetic_Study_of_Kitchen_Waste_Anaerobic_Digestion [07 March 2022].

Ang, T. *et al.* 2022. A comprehensive study of renewable energy sources: Classifications, challenges and suggestions. *Energy Strategy Reviews*, 43(November 2021): 100939. https://doi.org/10.1016/j.esr.2022.100939 [25 May 2023]

Bridgwater, A. V. and D.G, E. 1993. An assessment of thermochemical conversion systems for processing biomass and refuse: 251.

Cesaro, A. and Belgiorno, V. 2015. Opportunities and Challenges for Industrial Application. Energies, 8: 8121–8144. Doi: 10.3390/en8088121 [04 September 2022]

Çetinba, I., Demirta, M. and Tamyürek, B. 2019. Design, Analysis and Optimization of a Hybrid Microgrid System Using HOMER Software*. International Journal of Renewable Energies Development*, 8(1): 65–79. https://www.researchgate.net/publication/330835266_Design_Analysis_and_Optimization_of_a_Hybrid_Microgrid_System_Using_HOMER_Software_Eskisehir_Osmangazi_University_Example [22 August 2023]

Çetinbaş, İ., Tamyürek, B. and Demirtaş, M. 2019. Design, analysis and optimization of a hybrid microgrid system using HOMER software. *International Journal of Renewable Energies Development*, 8(1): 65–79. Doi: 10.14710/ijred.8.1.65-79 [17 June 2022]

Chakraborty, S. *et al.* 2012. Biomass to biofuel: a review on production technology. *Asia Pacific Journal of Chemical Engineering,* 7: 254–262. Doi: 10.1002/apj.1642 [05 February 2023]

Chiappero, M. *et al.* 2020. Review of biochar role as additive in anaerobic digestion processes. *Renewable and Sustainable Energy Reviews*, 131. https://doi.org/10.1016/j.rser.2020.110037 [26 August 2023]

Curry, N. and Pillay, P. 2012. Biogas prediction and design of a food waste to energy system for the urban environment, *Renewable Energy*, 41: 200–209. Doi: 10.1016/j.renene.2011.10.019 [June 2022]

Dahunsi, S. O., Fagbiele, O. O. and Yusuf, E. O. 2020. Bioenergy technologies adoption in Africa: A review of past and current status. *Journal of Cleaner Production, 264*. https://doi.org/10.1016/j.jclepro.2020.121683 [11 October 2022]

Damartzis, T. and Zabaniotou, A. 2011.Thermochemical conversion of biomass to second generation biofuels through integrated process design-A review. *Renewable and Sustainable Energy Reviews*, 15(1): 366–378. https://doi.org/10.1016/j.rser.2010.08.003 [02 November 2022]

David, E. *et al.* 2019. Biomass - alternative renewable energy source and its conversion for hydrogen rich gas production, 01001: 1–5. https://doi.org/10.1051/e3sconf/201912201001 [17 March 2023]

Elhouri, S. A. 2016. Renewable Energy Advantages & Disadvantages. *International Journal of research science and management,* 3(1): 1–4.

Abu-rub, H. Blaabjerg, F. and Ellabban, O. 2014. Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, 39: 748–764. https://doi.org/10.1016/j.rser.2014.07.113 [17 June 2022]

Elsamadony, M. *et al.* 2021. Advances towards understanding long chain fatty acids-induced inhibition and overcoming strategies for efficient anaerobic digestion process. *Water Research*, 190. https://doi.org/10.1016/j.watres.2020.116732 [19 February 2023]

Fatehi, H. *et al.* 2021. Recent development in numerical simulations and experimental studies of biomass thermochemical conversion. *Energy and Fuels*, 35(9): 6940–6963. Doi: 10.1021/acs.energyfuels.0c04139 [14 July 2022]

Chen, H. and Gao, C. 2023. Electricity from renewable energy resources: Sustainable energy transition and emissions for developed economies. *Utilities Policy*, 82. Doi: 10.1016/j.jup.2023.101543 [September 2022]

Goss, H. 2022. Limpopo Provincial Spatial Development Framework report.

Halkos, G. E. 2020. Reviewing Usage, Potentials, and Limitations of Renewable Energy Sources. Energies, 13. Doi:10.3390/en13112906 [August 2022]

Hanisah, W. and Ibrahim, W. 2019. Anaerobic Digestion Process of Food Waste for Biogas Production: A Simulation Approach, 42 (9): 1834–1839. Doi: 10.1002/ceat.201800637 [19 June 2023]

Hasan, M. R. 2019. Feasibility study to design a Biogas- Photovoltaic hybrid system for electricity generation in vicinity to urban areas in Bangladesh. Master's Thesis, Halmstad University.

Holt, A. and Pengelly, I. J. 2008. Energy Efficiency and Renewable Energy, 6: 3854–3862. Doi: 10.1049/ic.2008.0789 [13 March 2023]

Houcque, D. 2005. Introduction to MATLAB for Engineering Students, *School of Engineering & Applied Science*, (August): 1–74.

Hunt, B. R. *et al.* 2006. A Guide to MATLAB: For Beginners and Experienced Users: 328. Available at: http://www.amazon.co.uk/Guide-MATLAB-Beginners-Experienced-Users/dp/0521615658 [06 April 2023]

Ibrahim, I. D. *et al.* 2021. A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study. *Energy Strategy Reviews*, 38(August 2019): 100740. https://doi.org/10.1016/j.esr.2021.100740 [08 August 2023]

Ilo, O. P. *et al.* 2021. Methodological approaches to optimising anaerobic digestion of water hyacinth for energy efficiency in south Africa. *Sustainability (Switzerland)*, 13(12). https://doi.org/10.3390/su13126746 [25 July 2023]

Jahns, B. S. 2023. How Has the Current Electricity Crisis in South Africa Affected the Development of Renewable Energy within the Independent Power Producer Procurement Programmes, School of economics and management.

Jekayinfa, S. O. Orisaleye, J. I. and Pecenka R. 2020. An Assessment of Potential Resources for Biomass Energy in Nigeria. Resources: 1–41.

Jha, S. *et al.* 2022. A Review of Biomass Resources and Thermochemical Conversion

Technologies. *Chemical Engineering and Technology*, 45(5): 791–799. https://doi.org/10.1002/ceat.202100503 [17June 2022]

Adaramola, M. S. and Kemausuor, F. 2018. A Review of Commercial Biogas Systems and Lessons for Africa*. Energies,* 11(11): 1–21. https://doi.org/10.3390/en11112984 [13 March 2023]

Adaramola, M. S. Kemausuor, F. and Morken, J. 2018. A Review of Commercial Biogas Systems and Lessons for Africa. *Energies*, 11(11)1–21. Doi: 10.3390/en11112984 [14 March 2023]

Khan, S. *et al.* 2015. Biomass as Renewable Energy. *International Advanced Research Journal in Science, Engineering and Technology*, 2(1): 301–304.

Kothari, R. *et al.* 2014. Different aspects of dry anaerobic digestion for bioenergy: An overview. *Renewable and Sustainable Energy Reviews*, 39: 174–195. Doi: 10.1016/j.rser.2014.07.011 [18 July 2022]

Ackah, C. G and Kupzig, N. 2023. The Effect of an Electricity Crisis on Firms – A Case Study of Dumsor in Ghana. *SSRN Electronic Journal*: 1–17. Doi: 10.2139/ssrn.4440773 [13 June 2022]

Computing, T. and Language, T. 2004. MATLAB The Language of Technical Computing. *Components*, 3(7): 750. Doi: 10.1007/s10766-008-0082-5 [30 August 2023]

Lee, S. Y. *et al.* 2019.Waste to bioenergy: a review on the recent conversion technologies. *BMC Energy*, 1(1): 1–22. Doi: 10.1186/s42500-019-0004-7 [02 November 2022]

Li, W. *et al.* 2023. A review of high-solid anaerobic digestion (HSAD): From transport phenomena to process design. *Renewable and Sustainable Energy Reviews*, 180. Doi: 10.1016/j.rser.2023.113305 [17 July 2023]

Li, Y., Chen, Y. and Wu, J. 2019. Enhancement of methane production in anaerobic digestion process: A review. *Applied Energy*, 240: 120–137. Doi: 10.1016/j.apenergy.2019.01.243 [05 July 2023]

Mkhabela, N. K., Mukumba, P. and Makaka, G. 2020.Techno-Economic Aspects of Electricity Generation from A School Biogas Digester', (August).

Mukumba, P., Makaka, G. and Mamphweli, S. 2017. Biogasification of Horse Dung Using a Cylindrical Surface Batch Biodigester, *Frontiers in Bioenergy and Biofuels*, (September). Doi: 10.5772/65373 [04 August 2023]

South Africa. Municipality, M. and Plan, I. D. 2017. *Makhado Municipality Integrated Development Plan.* Limpopo. https://www.makhado.gov.za/sstaff/pages/sites/makhado/documents/idp/DRAFT%20INTERGRATED%20DEVELOPMENT%20PLAN%20%202022%20-2027.pdf [20 October 2022]

Mwangomo, E. A. 2018. Potential of Waste to Energy in African Urban Areas. *Advances in Recycling & Waste Management*, 03(02). https://www.researchgate.net/publication/329889105_Potential_of_Waste_to_Energy_in_African_Urban_Areas [14 February 2023]

Converti, A. das Neves, L. C. M. and Penna, T. C. V. 2009. Biogas production: new trends for alternative energy sources in rural and urban zones. *Chemical Engineering and Technology*, 32(8): 1147–1153. https://www.researchgate.net/publication/229641965_Biogas_Production_New_Trends_for_Alternative_Energy_Sources_in_Rural_and_Urban_ZonesOlugasa, T. T., Odesola, I. F. and Oyewola, M. O. (2014) 'Energy production from biogas: A conceptual review for use in Nigeria', *Renewable and Sustainable Energy Reviews*, 32, pp. 770–776. doi: 10.1016/j.rser.2013.12.013 [03 May 2023].

ETSU. Pointon, K. and Langan, M. 2002. Distributed power generation using biogas fuelled microturbines. https://www.osti.gov/etdeweb/servlets/purl/20350865 [22 August 2021]

Pramanik, S. K. *et al.* 2019.The anaerobic digestion process of biogas production from food waste: Prospects and constraints. *Bioresource Technology Reports*, 8. https://doi.org/10.1016/j.biteb.2019.100310 [06 June 2023]

Sinden, E. 2022. An assessment of household food wastage: A study of Wallacedene in Kraaifontein. Unpublished master's thesis, University of Western Cape, Bellville. Available at: https://etd.uwc.ac.za/handle/11394/9238%0Ahttps://etd.uwc.ac.za/bitstream/handle/11394/9238/madondo_m_ems_2022.pdf?sequence=1&isAllowed=y [02 March 2023]

Singh, A., Baredar, P. and Gupta, B. 2015. Computational Simulation & Optimization of a Solar, Fuel Cell and Biomass Hybrid Energy System Using HOMER Pro Software. *Procedia Engineering*, 127: 743–750. Doi: 10.1016/j.proeng.2015.11.408 [17 July 2023]

Stecher, K., Brosowski, A. and Thran, D. 2013. BIOMASS POTENTIAL IN AFRICA. International Renewable Energy Agency. https://www.researchgate.net/publication/298403255_Biomass_potential_in_Africa [02 March 2022]

Steinhauser, A. 2011. Potential for transforming biomass into end-point energy sources. *Wiley-VCH Verlag GmbH &Co. KGaA*. Biogas from waste and renewable resources. Germany: 11-37. https://www.academia.edu/2300641/Biogas_from_waste_and_renewable_resources_An_introduction [02 September 2021]

Surroop, D., Bundhoo, Z. M. A. and Raghoo, P.2019. Waste to energy through biogas to improve energy security and to transform Africa' s energy landscape. *Science direct.* 18: 79–83. Doi: 10.1016/j.cogsc.2019.02.010 [14 June 2023]

Tagne, R. F. T. *et al.* 2021.Technologies, challenges and perspectives of biogas production within an agricultural context. The case of China and Africa. *Environment, Development and Sustainability*, 23(10): 14799–14826. Doi: 10.1007/s10668-021-01272-9 [21 July 2023]

Tan, J. B. *et al.* 2021.Techno-Economic Assessment of On-Farm Anaerobic Digestion System Using Attached-Biofilm Reactor in the Dairy Industry. Sustainability, 13: 1–15. https://doi.org/10.3390/ su13042063 [22 June 2023]

Rural energy and development. 2005. *Rural Energy and Development for Two Billion People meeting the challenge*. Washington DC. The World Bank.

U.S. Environmental Protection Agency. 2014. Combined Heat and Power - A Guide to Developing and Implementing Greenhouse Gas Reduction Programs: 36. Available at: http://www3.epa.gov/statelocalclimate/documents/pdf/CHPguide508.pdf [03 April 2023]

Uddin, W. *et al.* 2016. Biogas potential for electric power generation in Pakistan: A survey. *Renewable and Sustainable Energy Reviews*, 54: 25–33. https://doi.org/10.1016/j.rser.2015.09.083 [18 July 2023]

W, P. 2009. Biogas technology in sub-Saharan Africa: Status, prospects and constraints. *Reviews in Environmental Science and Bio/Technology*, 8: 187 DOI: 10.1007/s11157-009-9148-0 [06 July 2023]

Wang, Z. *et al.* 2020.Biomass energy production and its impacts on the ecological footprint: An investigation of the G7 countries. *Science of the Total Environment*: 140741. https://doi.org/10.1016/j.scitotenv.2020.140741 [08 May 2023]

Wasif, M. *et al.* 2021. Effects of biomass energy consumption on environmental quality: The role of education and technology in Asia-Pacific Economic Cooperation countries. *Renewable and Sustainable Energy Reviews*, 142(February): 110868. https://doi.org/10.1016/j.rser.2021.110868 [10 May 2023]

World Bank Group. 2017.*STATE OF REPORT 2017 ELECTRICITY ACCESS*. Available at: www.worldbank.org [18 November 2022]

World Health Organisation. 2009. The Energy Access Situation in Developing Countries. *UNDP WHO New York*, (November): 142. Available at: https://www.undp.org/publications/energy-access-developing-countries [05 December 2022]

Zalm, J. 2017. Performance of domestic biodigesters in Kenya: Towards the development of a comparative method for measuring the performance of different biodigester types in Sub-Saharan Africa. Master's thesis, *Universiteit Utrecht*. https://studenttheses.uu.nl/bitstream/handle/20.500.12932/28209/MasterThesisJelleZalm.pdf?sequence=1&isAllowed=y [28 August 2023]